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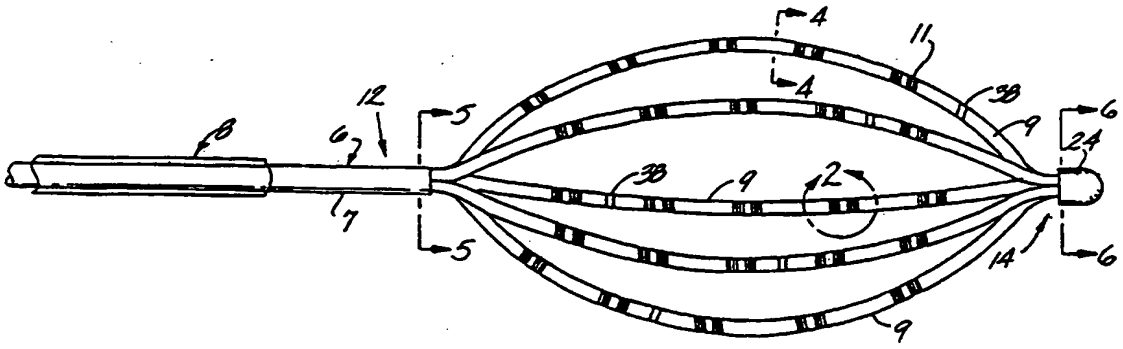

(57) Abstract

An electrophysiological mapping device includes an outer catheter (8), an inner catheter (6) slidable within the outer catheter, and an electronic activation and recording device (4) for electrically activating electrodes (11) on the inner catheter and/or recording electric signals received by the electrodes. The distal end of the inner catheter comprises a plurality of arms (9) that cary electrodes. The arms bow outwardly upon extension of the inner catheter from the outer catheter to form a three-dimensional shape. Each arm has a spine (25) of a super-elastic material. Each spine is semicircular in section, and is disposed within a portion of a flexible sheath (18), the electrode lead wires being disposed in the rest of the sheath. The electrodes are formed from the ends of the insulated electrode lead wires (20) which pass through the sheath, are wrapped around the sheath and then stripped of their insulation.

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UNIQUE ELECTRODE CONFIGURATIONS FOR CARDIOVASCULAR ELECTRODE CATHETER WITH BUILT-IN DEFLECTION METHOD AND CENTRAL PULLER WIRE

Field of the Invention

The present invention relates to cardiovascular catheters and, in particular, to such catheters having a retractable basket-shaped electrode array formed by a plurality of arms, each arm supporting a plurality of spaced-apart electrodes.

Background of the Invention

Electrophysiology is a specialty within the field of cardiology for diagnosis and treatment of electrical abnormalities of the heart. Diagnosis is performed using electrode-bearing catheters placed within the heart chambers. Electrodes are positioned along a catheter shaft in a primarily two-dimensional array, although electrode elements spaced laterally around the catheter shaft give the array a very limited third dimension. Understandably, this third dimension is limited because of the small catheter shaft diameter required for such catheters as they are introduced into the heart via the veins and arteries of the body.

Electrical abnormalities are typically diagnosed by detecting the course of electrical activation paths along the endocardial surfaces of the heart chambers over time. To do this, the cardiologist may place several catheters within one or more chambers of the heart to get a better "picture" of this electrical activity. Sometimes this electrical activity is cyclical, i.e., repeats fairly well from heartbeat to heartbeat. In such cases, one catheter may serve to perform the diagnosis by moving the electrodes to various regions and then point-by-point comparing activation times with a reference. This reference may be the external EKG or another electrode catheter maintained in a stable position within a heart chamber.

However, certain types of electrical activity within a heart chamber are not cyclical. Examples include arterial flutter or arterial fibrillation, and ventricular tachycardia originating in scars in the wall of the ventricle that have resulted from infarcts. Such electrical activity is random from beat to beat. To analyze or "map" this type of electrical activity, the "picture" must be obtained during one beat. In other words, all the points of the map or picture must be obtained simultaneously within one-tenth of a second.

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One solution to improve mapping is disclosed in U.S. Patent Nos. 4,522,212 to Gelinas et al. and 4,699,147 to Chilson et al. which are incorporated herein by reference. In these patents, a catheter has, at its distal end, multiple lead-carrying arms which extend in a three-dimensional array, each arm having an inner central rib and electrodes spaced along its length. In Chilson et al., the arms are fixed at their distal end, but free to move within an outer catheter tube at their proximal end. The lead-carrying arms may be retracted into and extended from the outer catheter tube. The distal end of the catheter is directed to the designated areas of the heart and withdrawn, with the lead-carrying arms retracted within the outer catheter tube. Once at the designated areas, the arms are extended from the outer catheter tube to form a three-dimensional shape, referred to as an "elliptical envelope."

The catheter described in Chilson et al. is able to hold a large number of electrodes in different relative positions within a heart chamber. By this means, the cardiologist can obtain a map of electrical activity in one heartbeat by recording electrical signals from all the electrodes simultaneously. This is done by analyzing the spatial and temporal relationship of the electrical signals received at the electrodes.

By rotating the catheter and/or moving it longitudinally and recording electrical signals, a series of maps or pictures can be produced. A series of such pictures provides a "moving" picture of successive heartbeats, which may be able to better define the ectopic sites of activation or other activation pathways that contribute to the malfunction. This type of information may then allow the cardiologist to intervene with another catheter to destroy that causative tissue. Such destruction of heart tissue is referred to as "ablation," which is a rapidly growing field within electrophysiology and obviates the need for maximally invasive open heart surgery.

In Chilson et al. the arms are easily moved relative to each other and hence, the shape of the elliptical envelope varies from time to time and may vary even when positioned in one place due to the pumping heart chamber or the effect of rotation. Accordingly, the spatial relationship of the electrodes is subject to variation of unknown amounts. This, in turn, imparts a high degree of uncertainty or error in any map of electrical activity produced with the use of this catheter.

To obtain additional improvements in mapping, Chilson et al. and U.S. Patent Nos. 5,156,151 and 5,324,284 both to Imran, which are incorporated herein by reference, utilize an internal puller wire to expand and stabilize the

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three-dimensional shape. The puller wires of Chilson et al. and the Imran references extend through catheter lumens which are not sealed against the flow of blood at either the proximal or distal ends of the catheters, and the puller wires of Chilson et al. and Imran are not coated. Thus, the puller wire is in direct contact with the lead wires and/or the catheter wall. Because the Chilson et al. and Imran puller wire is in direct contact with the lead wires and/or the catheter wall, which are fixed relative to the puller wire, the puller wire can become impinged between the lead wires when the catheter is bent preventing translation of the puller wire through the lumen. Further, when the puller wire is in direct contact with the lead wires, the puller wire can wear off the insulation of the lead wires or even severe the lead wires thereby destroying the catheter. Because the distal end of the catheter is not sealed against the flow of blood or air, blood can infiltrate the lumens of the catheter thereby preventing effective cleaning and sterilization of the catheter for reuse, and air can be introduced through the catheter into a blood vessel or the heart creating a potentially fatal air embolism.

Summary of the Invention

The present invention provides an electrophysiological mapping catheter comprising an outer catheter and an inner catheter. The inner catheter comprises a tubular shaft extending longitudinally through the outer catheter tube. At the distal end of the shaft, there is a plurality of flexible arms, each arm carrying a plurality of spaced-apart electrodes. The flexible arms of the basket are fixed at their proximal ends to a proximal fitting and fixed at their distal ends to a distal fitting. The shaft is movable longitudinally within the outer catheter and the arms and electrodes can be retracted into and extended from the outer catheter tube. When the arms are extended out of the catheter tube, the arms flex outwardly to form a "basket," the electrodes forming a three-dimensional array.

Each arm comprises a reinforcing spine surrounded by a tubular flexible sheath having a generally circular cross-section. Each reinforcing spine preferably has a semicircular cross-section with the flat surface of the spine facing inwardly, i.e. toward the axis of the catheter. The spines preferably lie in the outwardly facing portion of the tubular sheath with the remainder of the tubular sheath filled by insulated electrode lead wires.

The electrodes are preferably formed on the arms by passing insulated lead wires through the wall of the tubular sheath, wrapping the wires around the tubular sheath and gluing it thereto. The insulation is then stripped off the outer

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surfaces of the lead wires which are wrapped around the sheath. The electrode lead wires extend from the arms through the proximal fitting and through the lumen of the inner catheter shaft to a stimulation and/or recording device.

The proximal and distal fittings include polygonal rod segments whose flat sides correspond in number to the number of spines and engage the flat surfaces of the spines. A clamping ring is positioned around the spines to hold them in proper orientation on the polygonal rod segment. In a preferred embodiment, the spines are formed out of a superelastic material, particularly a nickel-titanium alloy, with "shape memory." Such material returns to its bowed shape upon extension of the arms out of the outer catheter.

Also provided is a tubular catheter shaft with a plurality of arms forming a three-dimensional shape at the distal end of the catheter shaft. Each arm has at least one electrode with an electrode lead wire connected thereto. A puller wire extends through a lumen of the catheter and is attached to the distal end of the basket shape such that the basket shape can be expanded by a proximally directed force applied to the puller wire. The lumen of the catheter shaft is closed at the distal end. In another embodiment of the invention, the puller wire is coated.

Further provided is an electrode configuration having a plurality of continuous electrode arms forming a three-dimensional shape. Preferably, portions of the electrode arms are coated.

Still further provided is a method of coating the electrode arms in which a coating material is dissolved in a solvent to form a solution. The solution is applied to the electrode arm and cured thereon.

Brief Description of the Drawings

FIG. 1 is an enlarged view of the distal end of an inner catheter and an outer catheter with the inner catheter extended from the outer catheter, thus forming a basket of electrodes at the distal end of the inner catheter;

FIG. 2 is an enlarged view of an electrode pair from the circled portion labeled "2" in FIG. 1;

FIG. 3 is a longitudinal cross-sectional view of the distal end of the inner catheter shaft;

FIG. 4 is an enlarged transverse sectional view taken along line 4-4 of FIG. 1 and showing one arm of the basket of FIG. 1;

FIG. 5 is a transverse sectional view of a proximal fitting which has been taken along line 5-5 of FIG. 1;

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FIG. 6 is a transverse sectional view of a distal fitting of the basket of FIG. 1 taken along line 6-6 of FIG. 1;

FIG. 7 is a schematic view of the ten asymmetric positions of rotation;

FIG. 8 is a partial perspective and partial schematic view of an electrophysiological mapping system according to the invention, including an inner catheter, an outer catheter, and an activation and recording device, showing the inner catheter retracted within the outer catheter;

FIG. 9 is an elevational view of a catheter having a basket of electrodes in a relaxed position with a coated puller wire and a deflectable control handle for activation of the puller wire;

FIG. 10 is an elevational view of the basket of FIG. 9 in an expanded position;

FIG. 11a is a cross-sectional view taken along line 11-11 of FIG. 9 illustrating the proximal end of the basket;

FIG. 11b is a cross-sectional view taken along line 11-11 of FIG. 9 illustrating the proximal end of the basket and an alternate embodiment of the coating on the puller wire;

FIG. 12 is a cross-sectional view taken along line 12-12 of FIG. 9 illustrating the distal end of the basket;

FIG. 13 is an elevational view of an alternate electrode configuration;

FIG. 14 is an elevational view of another alternate electrode configuration;

FIG. 15 is an elevational view of still another alternate electrode configuration;

FIG. 16 is an elevational view of a further alternate electrode configuration;

FIG. 17 is a cross-sectional view taken along line 17-17 of the electrode in FIG. 16;

FIG. 18a is an elevational view of the electrode configuration of FIG. 16 having the proximal ends of the electrodes completely coated;

FIG. 18b is a cross-sectional view taken along line 18b-18b of the electrode in FIG. 18a;

FIG. 19a is an elevational view of the electrode configuration of FIG. 16 having the distal ends of the electrodes completely coated;

FIG. 19b is a cross-sectional view taken along line 19b-19b of the electrode in FIG. 19a; and

FIG. 19c is a cross-sectional view taken along line 19c-19c of the catheter in FIG. 19a.

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Detailed Description of the Preferred Embodiment

With reference to FIGS. 1, 2, and 8 a preferred electrophysiological mapping system is shown. The system includes an electronic stimulation and/or recording device, an inner catheter 6, and an outer catheter tube 8. Outer catheter tube 8 carries inner catheter 6 to a mapping site, e.g., within a heart chamber, and also serves to withdraw the inner catheter 6 from the mapping site. Inner catheter 6 is slidable longitudinally within outer catheter tube 8. FIG. 8 shows the mapping system, including electronic stimulation and/or recording device 4, and inner catheter 6 retracted within outer catheter tube 8.

Inner catheter 6 comprises an elongated, tubular catheter shaft 7 and five electrode carrying arms 9 at the distal end of the catheter shaft 7. Inner catheter 6 can be moved relative to outer catheter tube 8 between an extended position as shown in FIG. 1 wherein arms 9 extend completely out of the distal end of outer catheter tube 8 and a retracted position generally as shown in FIG. 8 wherein the arms 9 are retracted within the outer catheter tube 8. In the extended position, the arms 9 bow outwardly to define a "basket" structure.

Each arm 9 has its own spaced set of ten electrodes 11, shown herein as five bipolar electrode pairs. In the embodiment shown, the five electrode pairs are generally evenly spaced. It is understood, however, that the number and spacing of the electrodes may vary as desired. Further, single electrodes may be used rather than bipolar electrode pairs.

The arms 9 are fixed at their proximal ends to a proximal fitting, generally designated 12, and also fixed at their distal ends to a distal fitting, general designated 14. Proximal fitting 12 is, in turn, fixed to the distal end of the catheter shaft 7. The catheter shaft 7 comprises a central lumen 13 which extends from its proximal end to its distal end. The shaft 7 preferably comprises a tubular wall 10 of high-strength braided stainless steel or other high-strength wire or fiber, sandwiched between inner and outer layers of firm, yet flexible, polyurethane, for example, as disclosed in U.S. Patent Application No. 07/645,230, filed January 24, 1991, incorporated by reference herein. This high-torque shaft structure allows a physician to control the orientation of the electrode basket within the heart chamber by rotating the catheter shaft 7 where it enters the patient's body, which is usually at the groin or neck. The shaft 7 preferably further comprises a nylon stiffening sleeve 15 lining the interior of the tubular wall 10.

FIG. 4 is a sectional view of an arm 9. The arm 9 has an outer tube/sheath 18 of a flexible insulating material, e.g., a plastic such as flexible

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polyurethane tubing. Inside the plastic tubing are the plurality of electrode lead wires 20, each wire having an insulation coating 21 and a central conductive wire core 23. The wires 20 extend from the electrodes 11 through the plastic tubing 18 of the arms 9, through the proximal fitting 12 and lumen 13 of the shaft 7 to the stimulation and/or recording device 4. In this embodiment, there are fifty lead wires 20 which correspond to the ten electrodes 11 carried on each of the five arms 9. The number of electrodes and, hence, electrode lead wires may be varied as needed.

Referring to FIG. 3, the lead wires 20 are separated into five bundles 22, each bundle 22 containing the ten lead wires 20 which correspond to the ten electrodes 11 carried by each particular arm 9. At their proximal ends, the separate wire bundles 22 terminate in separate plug connectors 24, which are plugged into the activation and recording device 4 (FIG. 8). The total number of lead wires 20 in each bundle 22 is equal to the number electrodes 11 on each corresponding arm. Therefore, if there are 5 electrodes on each arm, there will be 5 leads in the corresponding bundle. If there are 5 electrode pairs, there will be 10 electrode leads in the bundle. Each bundle 22 of leads is contained in an insulated flexible tube, which in turn enters the plug connector.

With reference to FIG. 2, each electrode 11 is formed by passing a lead wire 20 through the outer sheath 18 of the arm 9. The wire 20 is wrapped tightly around the sheath 18 and glued and then the insulation coating from the outwardly facing surfaces of the lead wires, i.e. the surfaces which will contact the heart wall, is stripped to expose the metal of the lead wire.

It is preferable that the electrode lead wires 20 be of a metal which is inert in blood. MONEL 400, which is a trademark of Huntington Alloy Products Division of International Nickel Co., Inc., Huntington, West Virginia, is presently preferred. MONEL refers to a group of corrosion-resistant alloys of predominantly nickel and copper and very small percentages of carbon, manganese, iron, sulfur, and silicon. Some such alloys also contain a small percentage of aluminum, titanium, and cobalt. MONEL 400 has the additional benefit that it is not as easily visible under fluoroscopic x-ray as platinum. Therefore, the electrodes can be small and all of equal size and uniformly arranged.

With materials which are more radiopaque, even spacing of the electrode is not desirable because it is difficult to distinguish which arm is at which location. For example, in U.S. Patent No. 4,699,147 to Chilson et al., the electrodes on one arm are spaced unevenly with respect to the electrodes on

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each other arm. If the electrodes were spaced evenly in the device of Chilson et al., it would be difficult to identify which arm is which under x-ray. In the preferred embodiment of the present invention, the electrode pairs on each arm are able to be spaced evenly with respect to each other and are located on corresponding positions to the electrodes on each other arm, although uneven spacing on each arm and staggered spacing with respect to the electrodes on other arms is acceptable.

The even spacing of electrodes would normally result in difficulty determining which arm is at which location. However, in accordance with one aspect of the invention, markers 38, at different locations along each arm, such as in a staggered or spiral pattern, are positioned on the arms, respectively. These markers preferably are of a material which is easily identifiable under fluoroscopic x-ray, such as platinum, and are in the shape of a band or ring fixed around each arm.

The arms 9 are supported by a flexible rib or spine 25 having a semicircular cross-section which runs through the outer tube 18 as shown in FIG. 4. The spine 25 is preferably formed out of a superelastic material, such as a nickel-titanium alloy having about 54 to 57% nickel, preferably 55%, and the remainder is titanium, preferably 45%. Such materials exhibit "shape memory." That is, it can be deformed by an external stress, e.g. bent, and, when that stress is removed, it will return to its original shape. A presently preferred material is sold under the trademark NITINOL by U.S. NITINOL of Saratoga, California. Such a superelastic spine 25 allows the arms 9 of the basket to be retracted into and extended from the outer catheter tube 8 and otherwise subjected to bending, such as from the beating heart chamber, yet still return to its proper shape, even if extremely deformed.

The spine 25 preferably has an insulation coating 33, e.g., of polyurethane paint, to help hold it in place and shield it from the lead wires. The lead wires 20 and spine 25 are positioned in sheath 18 such that the spine 25 occupies the outwardly facing portion of the sheath 18, while the lead wires 20 occupy the inwardly facing portion of the sheath 18. The terms "outwardly" and "inwardly" are relative to an axis or centerline of the basket. Spines 25 having a semicircular cross-section are preferred over spines having circular cross-sections of the same cross-sectional area because they provide greater lateral stability, yet have sufficient flexibility for opening into the "basket" shape when the inner catheter 6 is extended out of and collapsed into outer catheter tube 8.

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The positioning of the electrode lead wires 20 in the inward portion of the tube 18 places the wires 20 away from the heart wall. This enables the wire portion used for the electrodes 11 to pass through the sheath 18 at a location remote from the heart wall and thereby provide a smoother electrode surface. The hole in the sheath 18 through which the lead wire 20 extends and lead wire terminus is preferably covered and secured with an adhesive, e.g., polyurethane, in a position where it will not be in contact with the heart chamber wall.

The metal portion of each spine 25 extends beyond the plastic tubing 18 at each end and attaches to the two fittings 12 and 14, as shown in detail in FIGS. 3-6. The proximal fitting 12 is formed by a polygonal rod segment 26 having an axial aperture 32 formed therein. The rod segment 26 is preferably metal. The number of sides of the polygonal rod segment 26 equal the number of spines 25. The flat surface of each spine 25 is positioned flat against the side of the polygonal rod segment 26 in the same orientation as the spines 25 are located in forming the basket.

An outer clamping ring 27, e.g., of metal, holds the spines 25 in place against the sides of the polygonal rod segment 26. An adhesive, such as polyurethane or epoxy, is preferably used to permanently fix the spines, polygonal rod segment 26, and clamping ring.

The proximal fitting 12 is fixedly mounted within the distal end of the inner catheter shaft 7, e.g., by epoxy, polyurethane or other adhesives. The distal end of the nylon sleeve 15 extends up to and butts against the proximal end of the polygonal rod segment 26 and clamping ring 27. The electrode lead wires 20 from each arm 9 pass through the axial aperture 32 in the polygonal rod segment 26 and then through the nylon sleeve 15.

Distal fitting 14 is generally the same as proximal fitting 12, in that it has a polygonal rod segment 29. The spines 25 are fixed to each side, respectively, of the polygonal rod segment 29 and are secured thereto by an outer clamping ring 30. However, no aperture is needed in segment 29 because no lead wires are present at the distal fitting. In addition, it is preferable to provide an outer plastic tip member 31, which is rounded in shape at its distal end, to help the inner catheter slide through arteries or veins with minimum trauma and to prevent trauma in the heart chamber. The tip member 31 may be fixed by using adhesive, e.g., epoxy or polyurethane.

The distal fitting 14 is the same size as or, if desired, may be of a smaller scale than proximal fitting 12. These fittings 12 and 14 hold the spines 25 in proper angular orientation with respect to each other, and thus maintain the

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proper spacing of the arms 9 and the proper orientation of the basket. This is important because the cardiovascular catheter is subjected to a pumping heart wall and must also be rotated during the electrophysiological mapping process. In addition, the spines 25 are subjected to bending and other forces during retraction into the outer catheter and extension therefrom.

The basket is shown with five arms 9, which is the most preferable number. As shown in FIG. 7, there are at least ten useful asymmetrical positions of rotation. That is, the arms are placed at a first position in the heart chamber where readings are taken, and then the basket is rotated 36° where readings are again taken. As will be understood by those skilled in the art, there are an infinite number of orientations but only a limited amount of obtainable data is useful. By the use of five arms, the basket very nearly appears round in rotation when viewed from the end. This feature greatly facilitates placement and control within a heart chamber because the heart chambers are not round, but are irregular.

A greater number of arms is not preferred because differentiation of electrodes becomes more difficult and the inner catheter is more difficult to fit within the outer catheter. A lesser number of arms is more practical in that it is smaller and easier to differentiate the electrodes, but is not preferred because mapping becomes more cumbersome.

In use, the inner catheter 6 is disposed within the outer catheter 8 for placement in a vein or artery and then subsequently into a chamber of the heart. The outer catheter 8 holds the arms 9 of the basket internally in a collapsed position so that the entire catheter, consisting of the inner catheter 6 and the outer or guiding catheter 8, can be passed down the vein or artery into the heart chamber. Once the distal ends of the catheters have reached the desired heart chamber in the appropriate position, the outer catheter 8 is withdrawn so that the arms 9 flex into their predetermined "basket" position. The electrodes 11 contact the walls of the heart chamber in this position. Additional outward movement of the arms and pressure against the heart wall can be gained by pushing forward on the inner catheter shaft 7 causing the basket to widen outwardly. When mapping has been completed, the outer catheter can be extended back over the basket to collapse the arms, and then ultimately be withdrawn with the arms therein.

The inner mapping or basket catheter, as described above, has several advantages. For example, fixing the spines of the basket at both their distal and

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proximal ends provides a very laterally stable basket. This stability is important to hold the catheter in stable position within a beating heart chamber.

The fittings which hold the distal and proximal ends of the spines together the flat sides of the spines mating with the flat sides of the polygon, ensure accurate arrangement of the arms in three dimensions.

The semicircular cross-section of the spines increases the lateral stiffness in comparison with a round cross-section of equal area, thereby increasing the lateral stability of the basket.

The use of superelastic material, such as NITINOL, for the spine 25 results in a basket that can be bent, collapsed, and twisted without appreciable permanent deformation. It is thus highly resilient.

The use of five basket arms in conjunction with a high-torque catheter shaft achieves a basket which can readily be controlled and oriented within the heart chamber.

The use of the semicircular cross-section for the spine further allows the spines to fill the outwardly facing portion of the arm tubing, thus leaving the inwardly facing portion for the lead wires. Lead wires can thus extend through the tubing, and after being wrapped around the tubing can terminate at locations along the inwardly facing side of the arms away from the heart wall. Each exit hole and terminus can be covered and secured by adhesive. Only the outwardly facing portions of the lead wire which is wrapped around the tubing need be scraped bare to form the electrode.

The electrodes can thus be made quite small and are readily distinguished fluoroscopically from the platinum ring markers. The ring markers readily identify each arm of the basket, as they are arranged in a staggered or spiral form on the different arms.

The basket which is formed as described is not only laterally stiff, but is also quite resilient and can form itself readily to the contour of the heart chamber, by pushing the inner catheter forward after the basket has been exposed to the heart chamber through the withdrawal of the outer catheter. This helps ensure that all electrodes make good contact with the endocardial surface and provide strong electrical recording signals.

Referring to FIG. 9, a further embodiment is shown wherein a puller wire, generally designated 40, extends through the catheter 42 and is fixed to the distal fitting 44 of the basket, generally designated 46. The puller wire extends out of the proximal end 48 of the catheter and is attached to a means for applying a proximally directed force to the puller wire. The preferred means for

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applying the proximal force is a deflectable control handle 50 of the type disclosed in U.S. Patent Nos. 4,960,134 and Re. 34,502 both to Webster, Jr., which are incorporated herein by reference. When the deflectable control handle is activated, the puller wire and the distal fitting to which the puller wire is connected are pulled proximally relative to the catheter thereby expanding the basket outwardly to the position shown in FIG. 10. The outward expansion of the basket forces the arms 52 against the chamber walls thereby impeding the motion of the arms relative to each other and resisting the shifting of the basket within the heart chamber.

The external portion 54 of the puller wire is covered with a polyurethane tube 56 which is sealed at the distal fitting 44 and the proximal fitting 58 of the basket. The polyurethane tube has a diameter between .02 and .03 inch and has flares 74 and 84 (see FIGS. 11a and 12) formed on each end by stretching the tube to form a reduced diameter portion in the center of the polyurethane tube. When the polyurethane is stretched the central stretched portion becomes elastic. Because the tube is sealed at both the distal and proximal fittings, the proximal portion of the tube tends to scrunch together into an accordion-like shape 60 which in no way inhibits or interferes with the normal functions of the catheter. The polyurethane tube which is easily cleaned and sterilized prevents blood from infiltrating the puller wire and from flowing by capillary action to the internal portion of the puller wire which is infeasible to clean and sterilize. Thus, the polyurethane tube allows the catheter to be cleaned and sterilized for reuse. The internal portion 62 (see FIGS. 11a and 11b) of the puller wire is coated with TEFLON® and covered with a TEFLON® sheath 64. The TEFLON coating acts as a lubricant inside of the TEFLON sheath, and the TEFLON sheath acts as a shield for the lead wires and prevents the puller wire from being impinged or pinched when the catheter is bent. Thus, the TEFLON sheath covers the puller wire preventing the puller wire from creating a large frictional force by contacting the lead wires and catheter wall. Therefore, the smooth TEFLON coated puller wire, with its low coefficient of friction, easily and smoothly slides within the TEFLON sheath relative to the lead wires and catheter walls, thereby reducing the amount of force necessary to expand the basket and allowing the puller wire to translate easily in the distal direction so that the basket is easily retracted into the outer catheter 66.

As previously stated, the puller wire is attached to the distal fitting and the polyurethane tube is sealably attached to the distal end of the sheath. The details of these connections are illustrated in FIGS. 11a, 11b and 12.

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Referring to FIG. 11a, the TEFLON sheath is sealably attached to the proximal flare 74 of the polyurethane tube 56. The polygonal rod segment 68 has an aperture 70 through which the lead wires 72 extend. The lead wires then extend into the arms 52. The portions of the arms and lead wires within the aperture and the clamping ring have been removed from FIG. 11a for clarity. The puller wire 40 and TEFLON sheath extend through the aperture 70 and out of the catheter. The polyurethane tube extends up to the proximal fitting and has a flair 74 at its proximal end. The TEFLON sheath extends into the flair of the polyurethane tube. The TEFLON sheath and the polyurethane tube form a circumferential lap joint which is welded 75 shut with polyurethane. The proximal fitting in the distal end of the catheter is sealed with a polyurethane seal 77 thereby preventing blood from entering the catheter. Thus, the catheter can be cleaned sterilized and reused. Further, the seal 77 prevents air from entering the heart, and thus, preventing potentially fatal air embolism. With the puller wire enclosed in the polyurethane tube, which is fixed to the distal end of the catheter, it is possible to seal the catheter without interfering with the function of the puller wire. That is, the puller wire can slide freely in a tube which is sealably fixed to the distal end of the catheter. Further the welded polyurethane seal 77 is not subject to failure because there is no packing through which the puller wire must pass.

FIG. 11b shows an alternate embodiment of the coated puller wire in which the TEFLON sheath extends all the way to the distal fitting of the basket and is sealably attached to the distal fitting. The polyurethane tube is preferred to the TEFLON sheath because the polyurethane tube is elastic, and hence, less of an accordion shape 60 is encountered with the use of the polyurethane tube.

Referring to FIG. 12, the distal polygonal rod segment 76 has a bore 78 into the proximal side of the fitting. The distal end of the puller wire is inserted through a crimping tube 80 which is a hollow twenty-seven (27) gauge needle. The distal end 82 of the crimping tube is then crimped onto the puller wire, and the distal end of the crimping tube is inserted into the bore of the distal polygonal rod segment and nonremovably soldered 85 therein. The polyurethane tube also has a flair 84 at its distal end which is fitted over the proximal end 86 of the crimping tube forming a lap joint between the crimping tube and the polyurethane tube. The polyurethane tube is then welded 83 to the crimping tube with polyurethane. The distal fitting is, therefore, sealed because the soldering of the crimping tube to the polygonal rod segment seals the distal end of the puller wire

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from the blood stream and the polyurethane tube is circumferentially welded to the crimping tube preventing blood from reaching the puller wire.

The bore is centrally located in the distal rod segment, and the aperture 70 through which the puller wire passes is so small relative to the basket that the puller wire is positioned substantially central with respect to the basket. Thus, the puller wire is coaxial with the central axis of the basket, and the outward expansion of the basket is, therefore, uniform.

In use, right heart catheterization is performed by inserting an introducer into the femoral vein. The introducer is then guided through the inferior vena cava, and into the right atrium, and if required, it is guided into the right ventricle. The basket catheter is then pushed through the introducer into the heart. Left heart catheterization is performed by inserting an introducer into the femoral artery. The introducer is then guided through the iliac artery, the aorta, through the aortic valve and into the left ventricle. In the alternative, a right sided approach can be used entering the left atrium transeptally. The basket catheter is then pushed through the introducer into the heart. The catheterization procedure can be performed with less difficulty and with less trauma to the blood vessels by the use of steerable catheters/introducers, and catheters/introducers with soft deformable tips. U.S. Patent No. 4,531,943 to Van Tassel et al., which is incorporated herein by reference, discloses a catheter with a soft deformable tip for reducing the trauma to the blood vessels during catheterization. U.S. Patent No. 5,045,072 to Castillo et al., which is incorporated herein by reference, discloses a flexible tip catheter. Further the catheters/introducers may have a predisposed bend or bends which, depending upon the type of catheterization to be performed, are bent in a certain direction to simplify that specific type of catheterization.

In FIGS. 13 through 16 alternate electrode configurations are illustrated which can be used for different types of ablation and mapping. After the required mapping has been performed and problematic areas are located, radio frequency can be provided to the electrodes of the existing catheter for ablation or if a specialized type of ablation is needed, the catheter may be removed and a catheter having an electrode arrangement such as that in FIG. 13 can be inserted into the introducer, properly oriented in the heart, and used to ablate the problematic tissue.

The electrode configuration of FIG. 13 provides a wide electrode array with a spiral pattern. The arms 88 have closely spaced electrodes 90 so that detailed mapping is obtained. The electrodes spiral down the arms 88 starting

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with arm 88A having electrodes in the most distal position then to arm 88B with the electrodes being slightly proximal of the electrodes on arm 88A. The electrodes on arm 88C are then slightly proximal of the electrodes on arm 88B, and the electrodes on arm 88D are just proximal of the electrodes on arm 88C. Finally, the electrodes on arm 88E are located just proximal of the electrodes on arm 88D, and thus, the arm 88E electrodes are the most proximal electrodes. An angle α is defined by a line 87 which is perpendicular to the axis of the catheter and a line 89 which is defined by the two most proximal electrodes on any two adjacent arms, except the A and E arms, and the angle α of the spiral can be adjusted to meet the specific mapping requirements. Thus, the electrodes can form a circle or a spiral which spans the entire length of the basket. This type of electrode configuration is especially useful for mapping atrial rhythms.

FIG. 14 illustrates an electrode configuration in which three rings 92A, 92B, and 92C of bipolar electrodes are placed around the arms 94 of the basket. This electrode configuration is especially useful for mapping and ablation in the right atrium. With the tip inserted into the coronary sinus opening, the most distal ring of electrodes 92C is positioned around the coronary sinus opening, and because the tip is inserted into the coronary sinus opening, the proximal ring of electrodes is located next to the edge of the coronary sinus opening. Thus, the right atrium can be accurately mapped around the coronary sinus opening, and if necessary, an ablation line can be made around the entire circumference of the coronary sinus opening. This method can be used with other openings in the walls of the heart chambers by adjusting the location of the distal ring 92C of electrodes. For openings having larger diameters, the distal ring would be moved proximally. Thus, the distal ring would have, when the basket is expanded, a diameter which is slightly greater than the diameter of the target opening. For openings having smaller diameters, the distal ring would be moved distally thereby reducing the diameter of the electrode ring when the basket is expanded.

FIG. 15 shows another alternate configuration of electrodes. A bipolar electrode 98 is placed on each arm 100. The electrodes form a narrow ablation line which spirals starting with the most distal electrode on arm 100A running to the next most proximal electrode on arm 100B to the middle electrode on arm 100C to the next most proximal electrode on arm 100D and finally to the most proximal electrode on arm 100E. Therefore, a thin ablation line is made which spirals from the distal electrode on arm 100A to the proximal electrode on arm 100E. An angle β is defined by a line 101 which is perpendicular to the axis of

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the catheter and a line 103 which is defined by the two most proximal electrodes on any two adjacent arms except the A and E arms, and the angle β of the spiral can be varied to meet specific ablation needs. Therefore, the electrodes can form a circle or a spiral which spans the entire length of the basket. The electrodes used in the embodiments of FIGS. 13-15 can be rings of any suitable electrically conductive material, but the rings are preferably fabricated from platinum or alloys of platinum and iridium.

FIG. 16 shows an alternate electrode configuration in which each arm 102 is an electrode over its entire length. Thus, the arm is a continuous electrode. Each arm comprises a NITINOL band or other inert conductive material having a generally semicircular cross section as shown in FIG. 17. The side 104 of the NITINOL band facing inwardly, that is, away from the wall of the heart chamber, is coated with a polyurethane coating 106 or other insulating material and thus, is a non-ablating area. The polyurethane, which has high viscosity and a short pot life, can be obtained from E.V. Roberts, Culver City, California by referencing the identification number RF-1737.

As shown in FIG. 17, the coating may also be applied to the edges 110 of the NITINOL band. Thus, the side 108 of the NITINOL wire facing the wall of the heart chamber is an exposed ablation area and can transmit radio frequency energy to the heart wall for ablation. This forms a long narrow ablation line along the length of the electrode. Depending on where the ablation is necessary, a different electrode arm is chosen for the ablation. Though the electrodes shown are semicircular in cross-section, other cross-sectional shapes such as circular or elliptical can be utilized. These cross-sectional shapes would have inner and outer faces corresponding to the inner and outer sides of the band.

The inward side 104 and the edges 110 are coated to prevent the radio frequency energy from creating a build up of blood on the band and to reduce the amount of radio frequency energy necessary to perform the required ablation. The maximum radio frequency energy which can be transmitted by the lead wires is limited by the heating of the lead wires. By reducing the radio frequency energy transmitted to the blood, longer ablation lines can be made because more of the maximum radio frequency energy which can be transmitted by the lead wires is used for ablation.

Further, greater or smaller portions of the electrodes can be coated. In an alternate embodiment shown in FIGS. 18a and 18b, the entire proximal half, generally designated 111, or part of the proximal end of each electrode arm is coated with a polyurethane coating 114. The distal half, generally designated

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116, has coating 118 on the inner side 120 and edges 122 leaving only the outer sides 112 of the distal half of the electrode arms uninsulated and available for ablation. Alternatively, as illustrated in FIGS. 19a, 19b and 19c, the entire distal half, generally designated 124, or part of the distal end of each electrode arm is coated with a polyurethane coating 126. The proximal half, generally designated 128, has coating 130 on the inner side 132 and edges 134 leaving only the outer sides 136 of the proximal half of the electrode arms uninsulated and available for ablation. Thus, it can be seen that any part of the electrodes can be coated depending on the requirements of specific ablation applications. These embodiments serve to localize the application of the radio frequency energy to the area needed thereby further reducing the amount of radio frequency energy transmitted to the blood and tissue which does not need to be ablated. Thus, the total amount of radio frequency energy needed for ablation is reduced.

As shown in FIG. 5, the electrode arms can be fixed to the proximal fitting 26 of the basket. The arms are then connected to the radio frequency generator with lead wires. This arrangement is preferred if a puller wire is used. However, referring to FIG. 19c, the electrode arms 146 can extend through the catheter 142 and connect directly to the radio frequency generator. The electrode arms inside the catheter 142 of this embodiment have an insulating sheath 148 similar to the sheath on the lead wires, and puller wire 144 extends through the catheter 142.

To apply the polyurethane coating to the NITINOL band, the polyurethane is dissolved in a solvent composed of approximately two parts tetrahydrofuran to one part p-dioxane which lowers the viscosity of the polyurethane for application to the electrode arm. Tetrahydrofuran can be obtained from Aldrich Chemical Co., Inc., Milwaukee, Wisconsin, and p-dioxane can be obtained from E.M. Science, Gibbstown, New Jersey. Once the polyurethane is completely dissolved in the solution, the solution is applied to the arms of the electrode to cover the non-ablating areas of the electrode arms discussed above. The solution can be applied by painting it onto the electrode with an artist's brush, dipping the electrode, submerging the electrode, or spraying the solution onto the electrode. Alternatively, the coating can be obtained by dipping the electrode in a latex solution and completely coating it with a very thin coating of an elastomer such as a polyurethane latex with a shore hardness of 50 D or less. The latex is then fully cured by heating in a dry oven. When the electrode arm is coated by submerging or dipping, the coating is removed from the ablating areas of the electrode by sandblasting with a Comco sandblaster using sodium

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bicarbonate which is directed in a well defined jet at the ablating areas of the electrodes. The jet of sodium bicarbonate removes the coating with high resolution leaving the electrode undamaged.

To assure the accurate application of the solution, the portions of the electrodes which are not to be coated can be covered with a tape 138 (see FIG. 19a) thereby preventing solution from directly contacting the electrodes in those areas. The tape 138 is adhesive on one side so that it can be added to the outer surface 136 of the electrodes, and it is fabricated from a material capable of withstanding the curing temperatures of the solution. The masking process simplifies the coating of electrodes having different cross-sections such as circular and provides a method for controlling the width of the ablation line. The electrode with the solutions thereon are then heated for approximately 2 hours at approximately 100°C or until the polyurethane has cured. Though polyurethane is preferred, other electrically insulating materials which are bio-compatible and maintain adhesion in the vascular system can be used. The tape is then removed after curing.

The invention has been described in its preferred embodiment. Numerous variations of the invention will be evident to those of ordinary skill in the art. The appended claims not only cover the preferred embodiment, but also such variations.

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WHAT IS CLAIMED IS:

1. A catheter for cardiac mapping and ablation comprising:
a catheter body having a distal end and a lumen;
a plurality of arms extending through the lumen and out the distal end of the catheter forming a three-dimensional shape; and
the arms comprising a continuous electrode.

2. The catheter of claim 1 wherein the arms have distal end and further comprising a distal fitting fixing the distal ends of the arms thereto.

3. The catheter of claim 1 wherein the arms have a portion inside the catheter body which is insulated.

4. A mapping and ablation catheter comprising:
a catheter body having a lumen and a distal end; and
a plurality of continuous electrode arms extending from the distal end of the catheter forming a three-dimensional shape.

5. A catheter basket electrode configuration for use with a catheter, the electrode configuration comprising a plurality of continuous electrode arms each arm having a proximal end and a distal end and the arms forming a three-dimensional shape.

6. The configuration of claim 5 wherein the proximal ends of the arms are fixed together and the distal ends of the arms are fixed together and the arms are expanded radially outward forming the three-dimensional shape.

7. The configuration of claim 5 wherein at least one arm is partially insulated.

8. The configuration of claim 5 wherein each arm is partially insulated.

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9. A method for coating a continuous electrode with an insulating coating comprising the steps of:

dissolving an insulator in a solvent to form a solution;

applying the solution to non-ablating areas of the continuous electrode; and

curing the solution with heat.

10. The method of claim 9 wherein the solvent is approximately one part p-dioxane and two parts tetrahydrofuran.

11. The method of claim 9 wherein the insulator is polyurethane.

12. The method of claim 9 wherein the solution is applied with an artist's brush.

13. The method of claim 9 wherein the solution is applied by dipping the electrode in the solution and further comprising the step of removing the cured coating from ablation areas of the electrode.

14. The method of claim 13 wherein the cured coating is removed with a high pressure solution propelled at the coating.

15. The method of claim 9 wherein the solution is applied by spraying the solution onto the electrode.

16. The method of claim 9 wherein the solution is applied to an inner surface of the electrode.

17. The method of claim 9 wherein the solution is applied to an inner surface of the electrode and to a proximal end of the electrode.

18. The method of claim 9 wherein the solution is applied to an inner surface of the electrode and to a proximal half of the electrode.

19. The method of claim 9 wherein the solution is applied to an inner surface of the electrode and to a distal end of the electrode.

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20. The method of claim 9 wherein the solution is applied to an inner surface of the electrode and to a distal half of the electrode.

21. A method for coating a continuous electrode comprising:

dipping the electrode in latex to form an insulating coating of the electrode;

curing latex with heat; and

removing the coating from the ablation areas of the electrodes.

22. The method of claim 21 wherein the coating is removed with a high pressure solution propelled at the coating.

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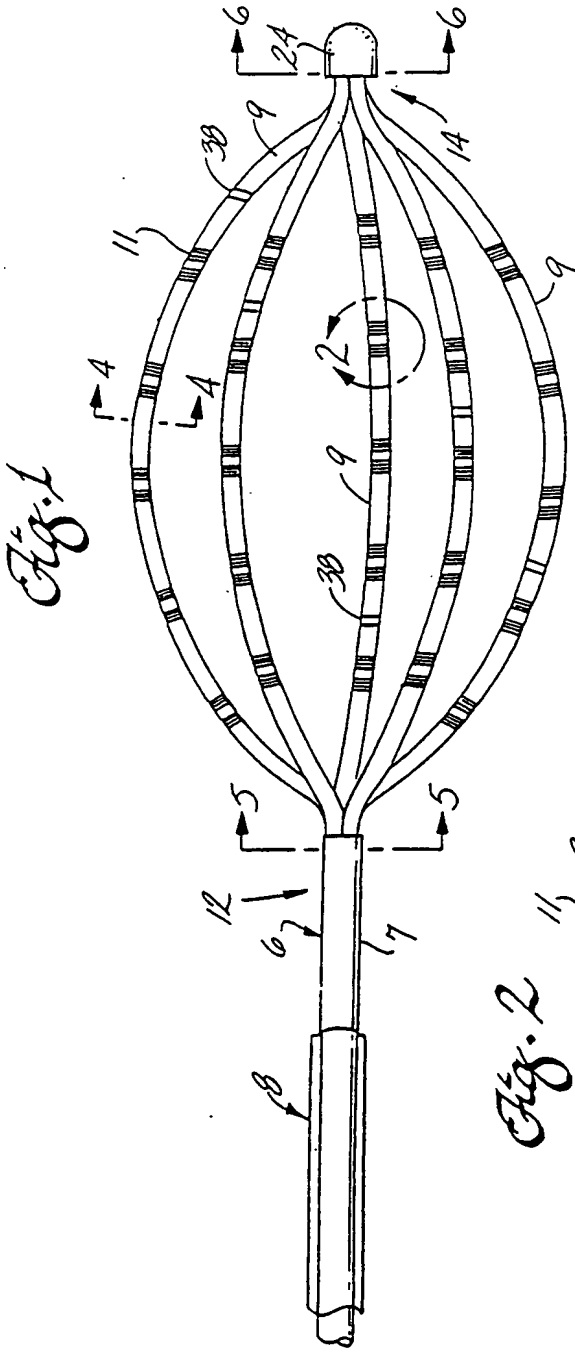

Fig. 1

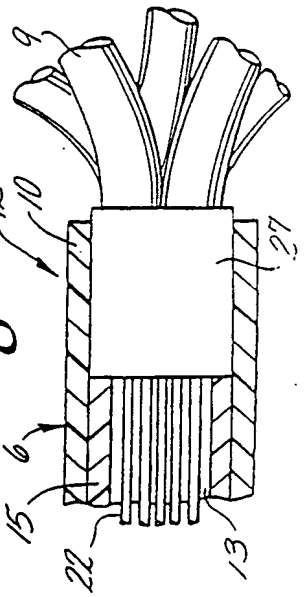

Fig. 3

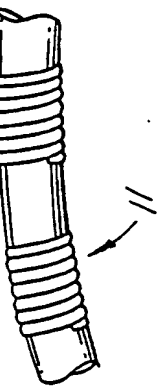

Fig. 2

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FIG. 4

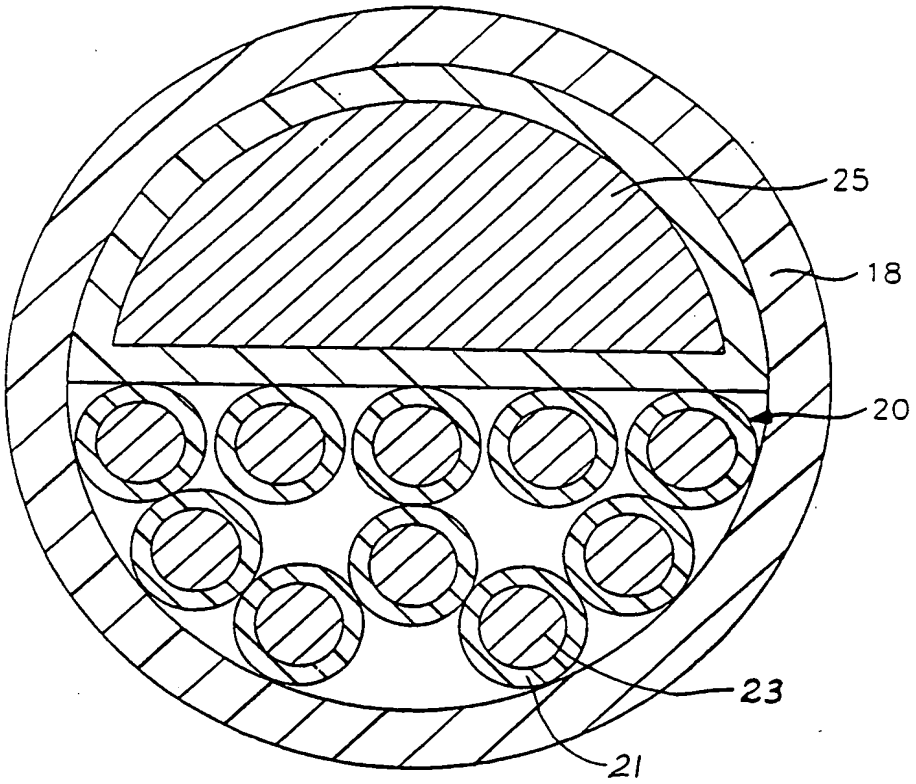

FIG. 5

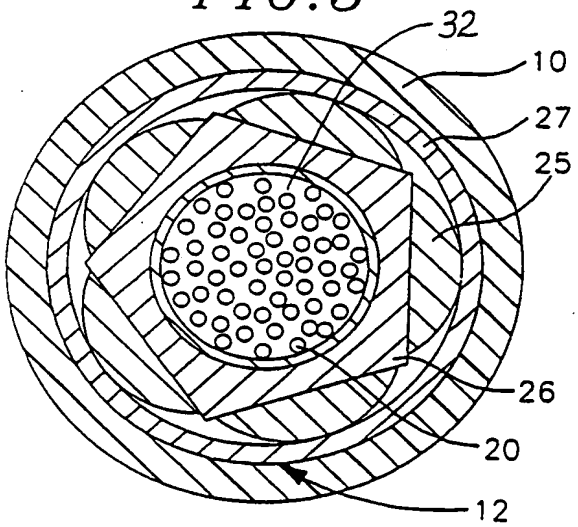

FIG. 6

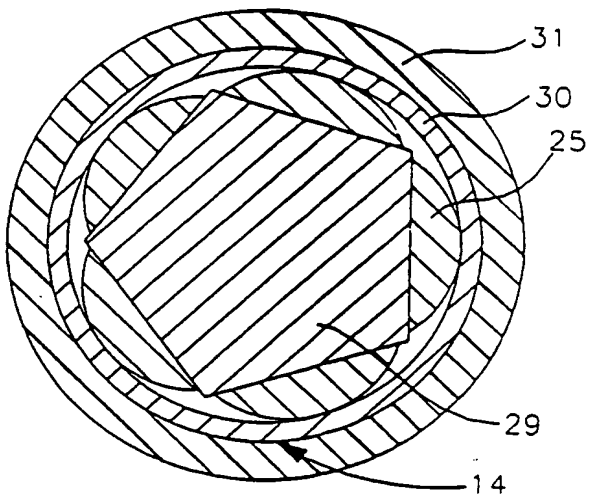

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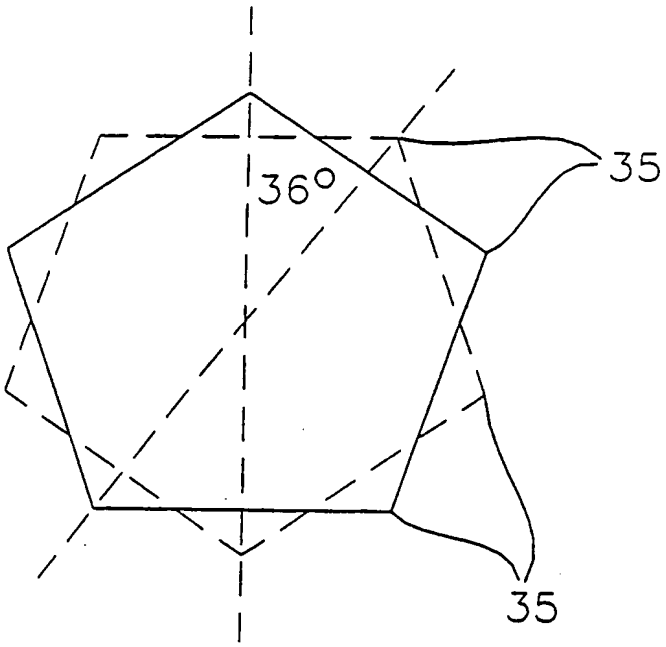
FIG. 7



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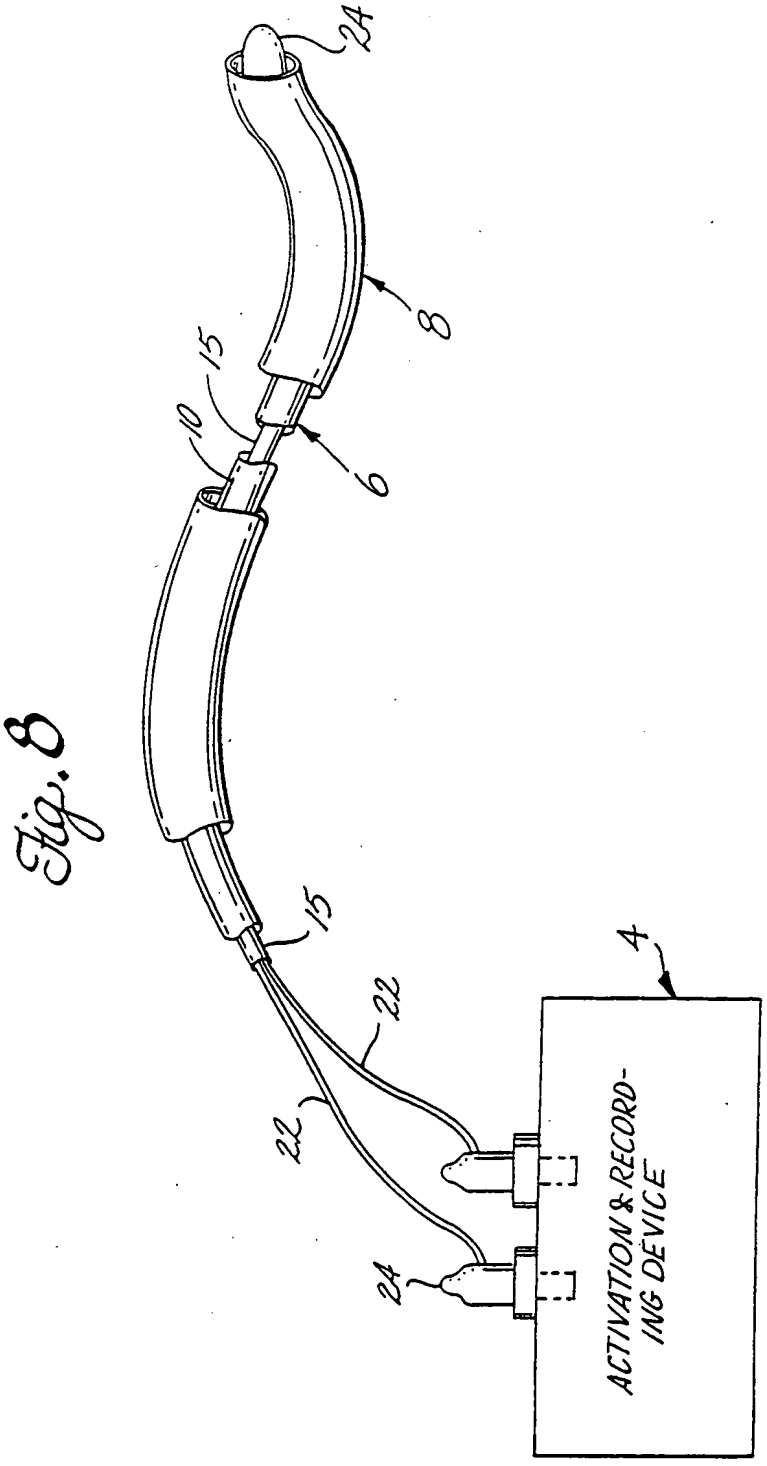

Fig. 8

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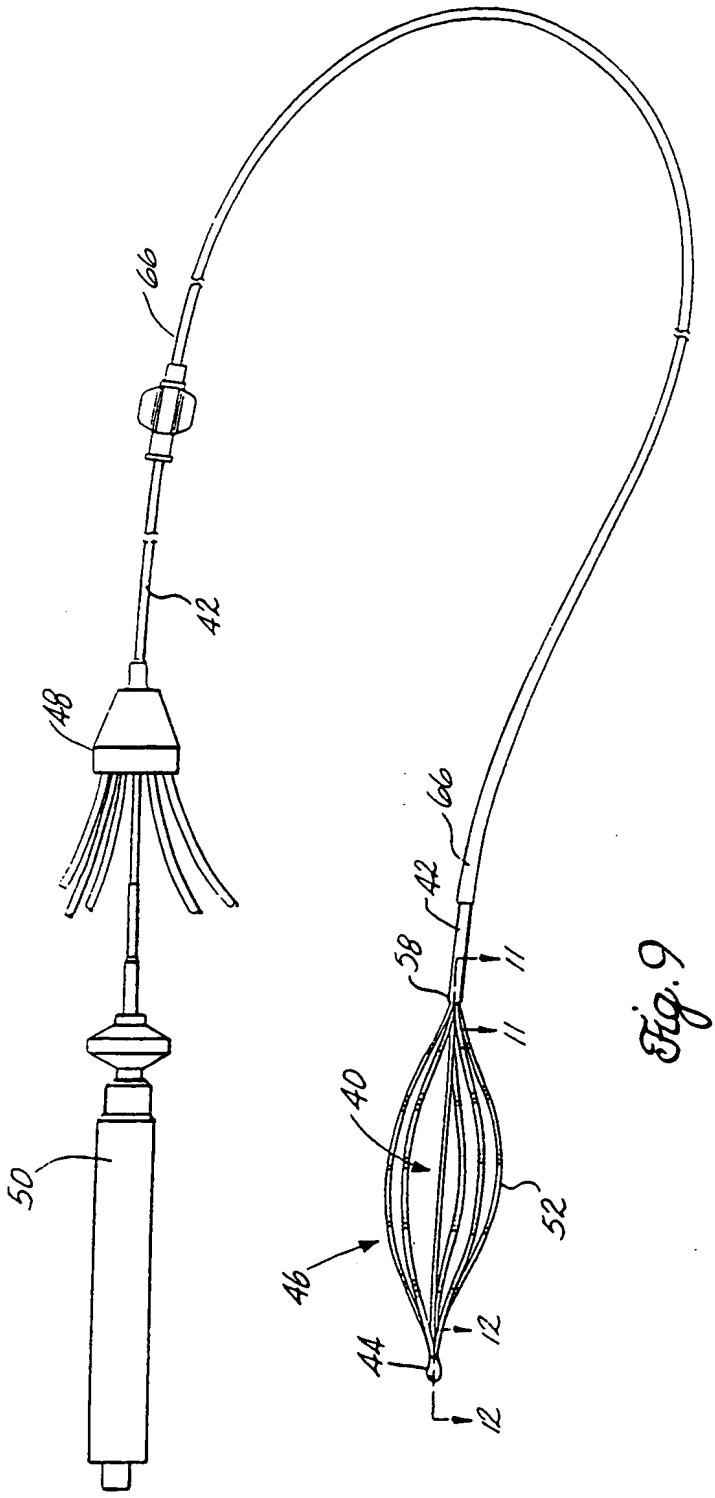

Fig. 9

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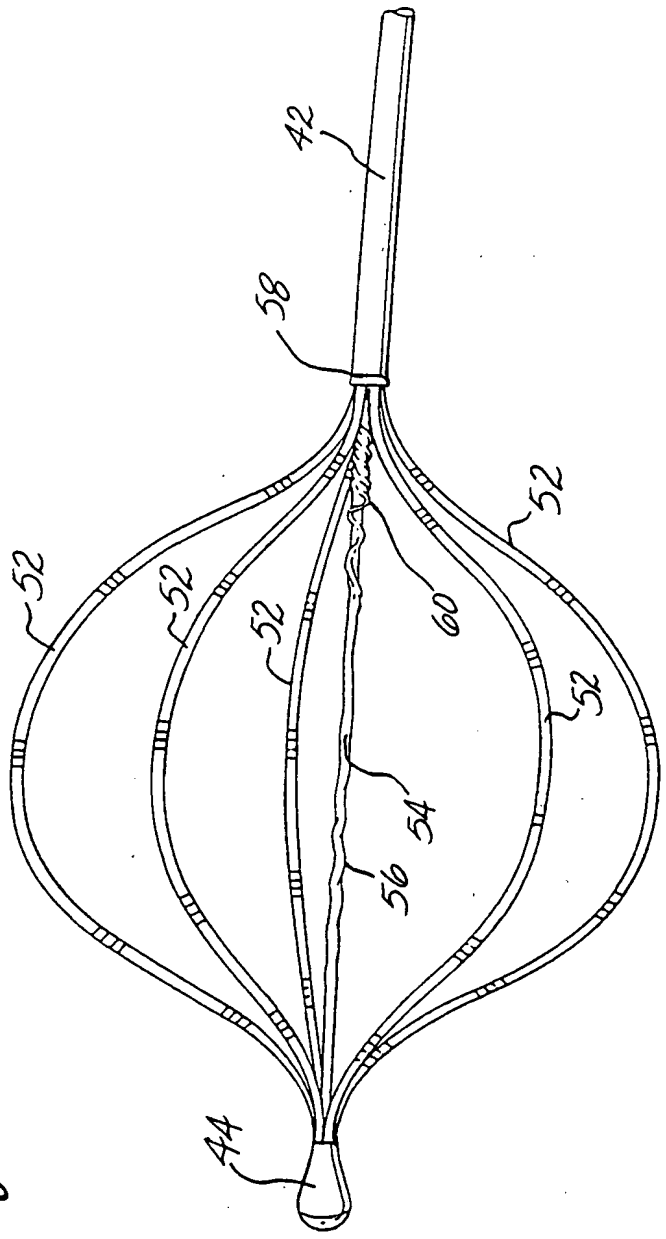

Fig. 10

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Fig. 11a

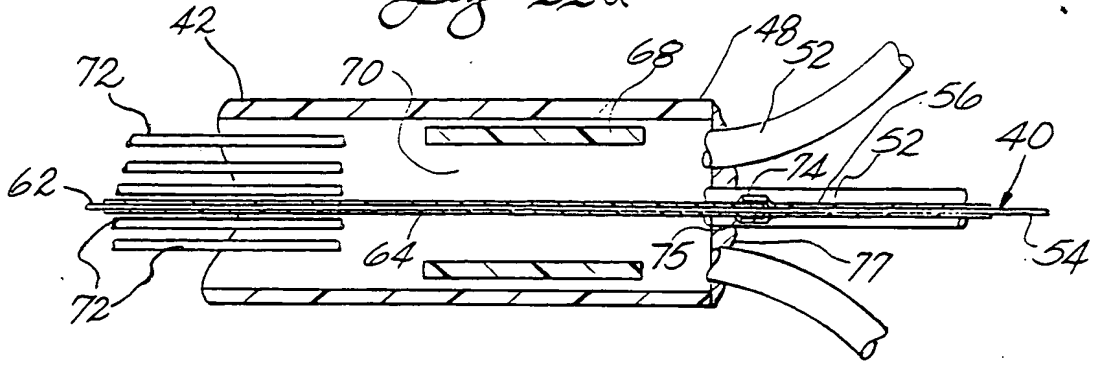


Fig. 11b

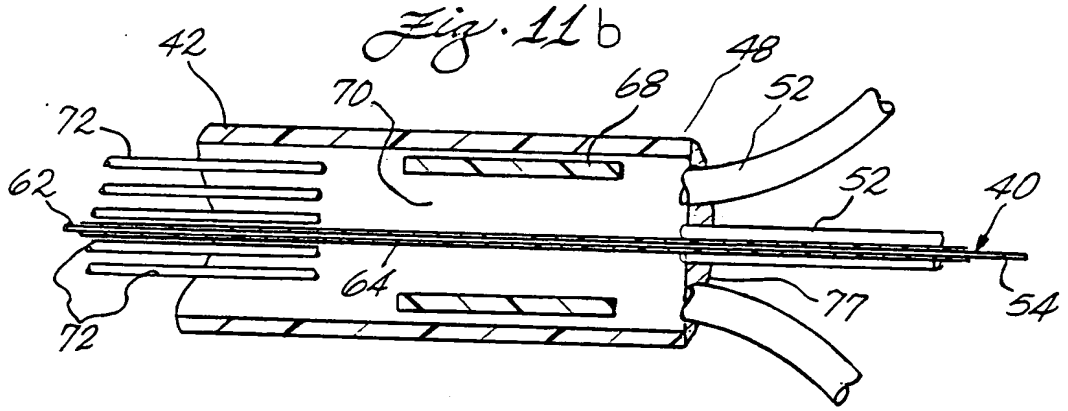
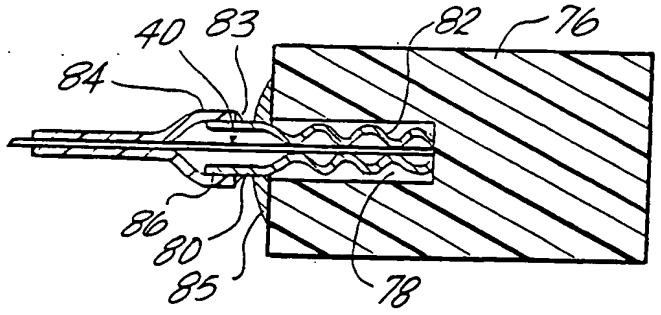


Fig. 12



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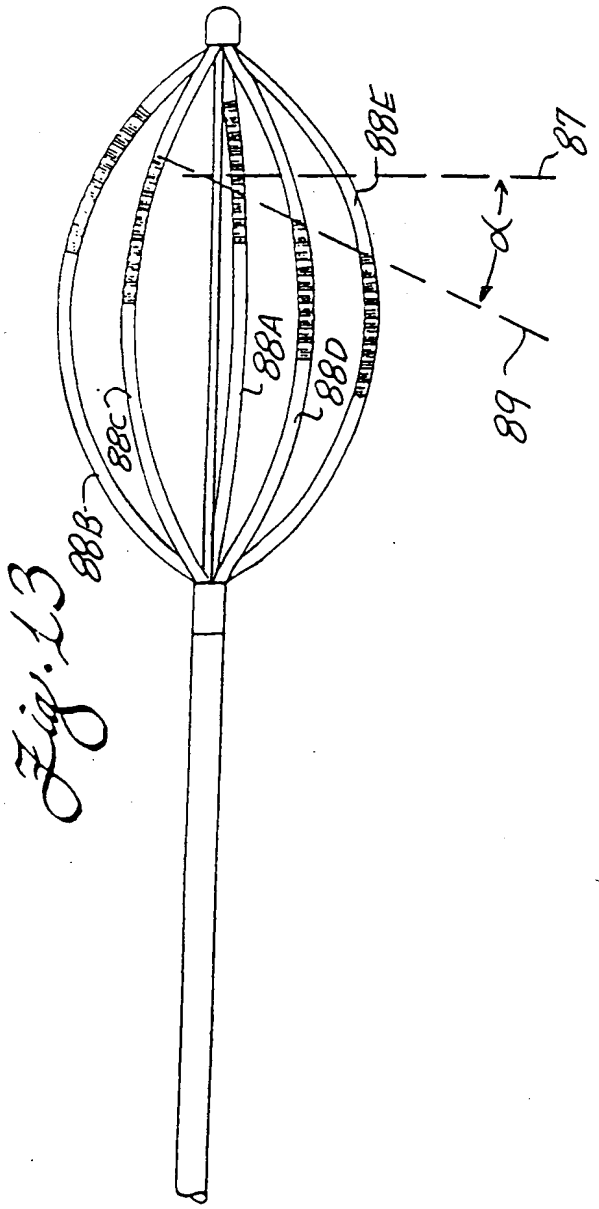

Fig. 13

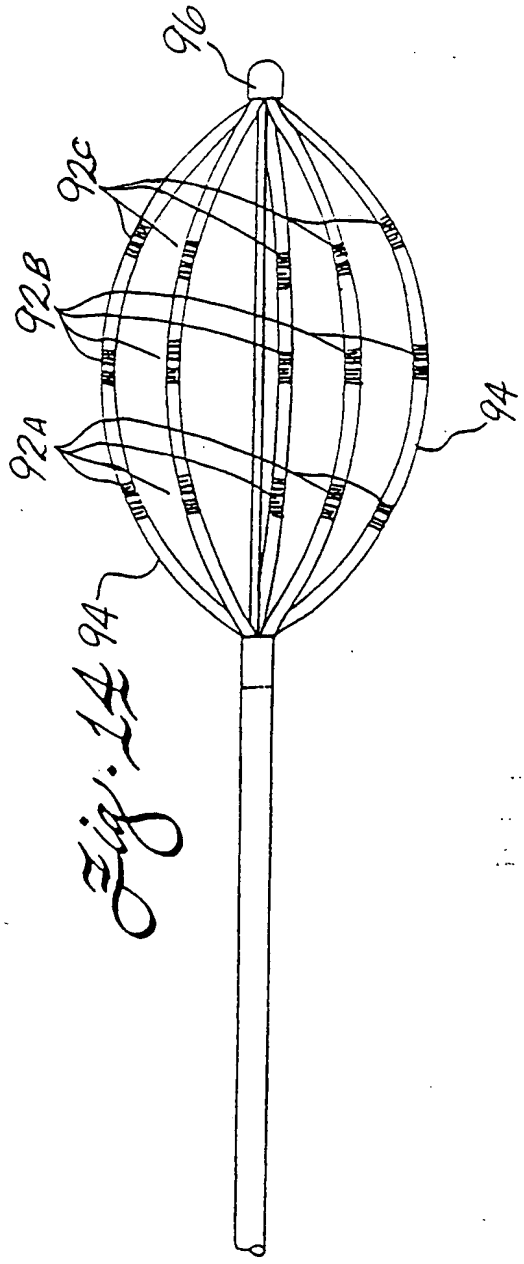

Fig. 14

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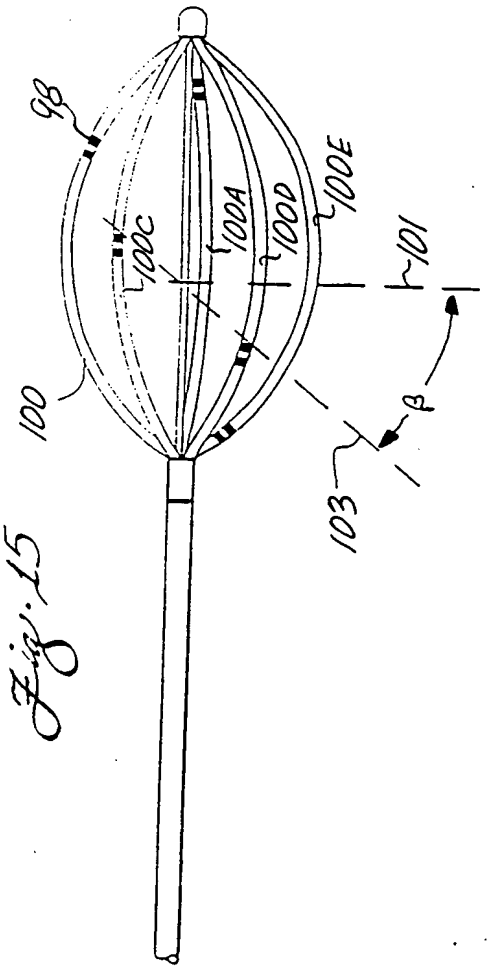

Fig. 15

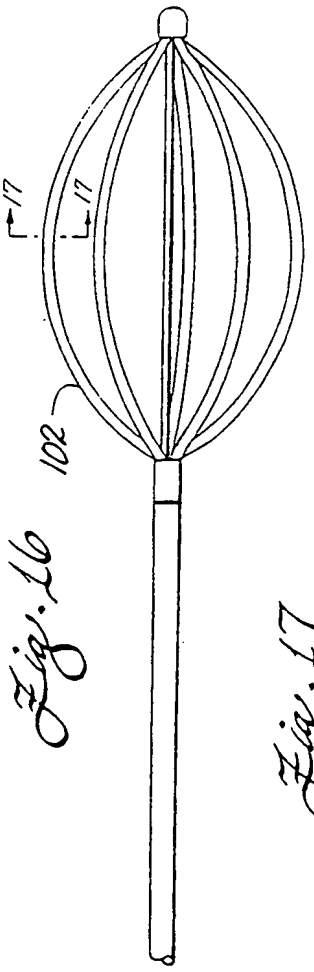

Fig. 16

Fig. 17

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The positioning of the electrode lead wires 20 in the inward portion of the tube 18 places the wires 20 away from the heart wall. This enables the wire portion used for the electrodes 11 to pass through the sheath 18 at a location remote from the heart wall and thereby provide a smoother electrode surface. The hole in the sheath 18 through which the lead wire 20 extends and lead wire terminus is preferably covered and secured with an adhesive, e.g., polyurethane, in a position where it will not be in contact with the heart chamber wall.

The metal portion of each spine 25 extends beyond the plastic tubing 18 at each end and attaches to the two fittings 12 and 14, as shown in detail in FIGS. 3-6. The proximal fitting 12 is formed by a polygonal rod segment 26 having an axial aperture 32 formed therein. The rod segment 26 is preferably metal. The number of sides of the polygonal rod segment 26 equal the number of spines 25. The flat surface of each spine 25 is positioned flat against the side of the polygonal rod segment 26 in the same orientation as the spines 25 are located in forming the basket.

An outer clamping ring 27, e.g., of metal, holds the spines 25 in place against the sides of the polygonal rod segment 26. An adhesive, such as polyurethane or epoxy, is preferably used to permanently fix the spines, polygonal rod segment 26, and clamping ring.

The proximal fitting 12 is fixedly mounted within the distal end of the inner catheter shaft 7, e.g., by epoxy, polyurethane or other adhesives. The distal end of the nylon sleeve 15 extends up to and butts against the proximal end of the polygonal rod segment 26 and clamping ring 27. The electrode lead wires 20 from each arm 9 pass through the axial aperture 32 in the polygonal rod segment 26 and then through the nylon sleeve 15.

Distal fitting 14 is generally the same as proximal fitting 12, in that it has a polygonal rod segment 29. The spines 25 are fixed to each side, respectively, of the polygonal rod segment 29 and are secured thereto by an outer clamping ring 30. However, no aperture is needed in segment 29 because no lead wires are present at the distal fitting. In addition, it is preferable to provide an outer plastic tip member 31, which is rounded in shape at its distal end, to help the inner catheter slide through arteries or veins with minimum trauma and to prevent trauma in the heart chamber. The tip member 31 may be fixed by using adhesive, e.g., epoxy or polyurethane.

The distal fitting 14 is the same size as or, if desired, may be of a smaller scale than proximal fitting 12. These fittings 12 and 14 hold the spines 25 in proper angular orientation with respect to each other, and thus maintain the

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proper spacing of the arms 9 and the proper orientation of the basket. This is important because the cardiovascular catheter is subjected to a pumping heart wall and must also be rotated during the electrophysiological mapping process. In addition, the spines 25 are subjected to bending and other forces during retraction into the outer catheter and extension therefrom.

The basket is shown with five arms 9, which is the most preferable number. As shown in FIG. 7, there are at least ten useful asymmetrical positions of rotation. That is, the arms are placed at a first position in the heart chamber where readings are taken, and then the basket is rotated 36° where readings are again taken. As will be understood by those skilled in the art, there are an infinite number of orientations but only a limited amount of obtainable data is useful. By the use of five arms, the basket very nearly appears round in rotation when viewed from the end. This feature greatly facilitates placement and control within a heart chamber because the heart chambers are not round, but are irregular.

A greater number of arms is not preferred because differentiation of electrodes becomes more difficult and the inner catheter is more difficult to fit within the outer catheter. A lesser number of arms is more practical in that it is smaller and easier to differentiate the electrodes, but is not preferred because mapping becomes more cumbersome.

In use, the inner catheter 6 is disposed within the outer catheter 8 for placement in a vein or artery and then subsequently into a chamber of the heart. The outer catheter 8 holds the arms 9 of the basket internally in a collapsed position so that the entire catheter, consisting of the inner catheter 6 and the outer or guiding catheter 8, can be passed down the vein or artery into the heart chamber. Once the distal ends of the catheters have reached the desired heart chamber in the appropriate position, the outer catheter 8 is withdrawn so that the arms 9 flex into their predetermined "basket" position. The electrodes 11 contact the walls of the heart chamber in this position. Additional outward movement of the arms and pressure against the heart wall can be gained by pushing forward on the inner catheter shaft 7 causing the basket to widen outwardly. When mapping has been completed, the outer catheter can be extended back over the basket to collapse the arms, and then ultimately be withdrawn with the arms therein.

The inner mapping or basket catheter, as described above, has several advantages. For example, fixing the spines of the basket at both their distal and

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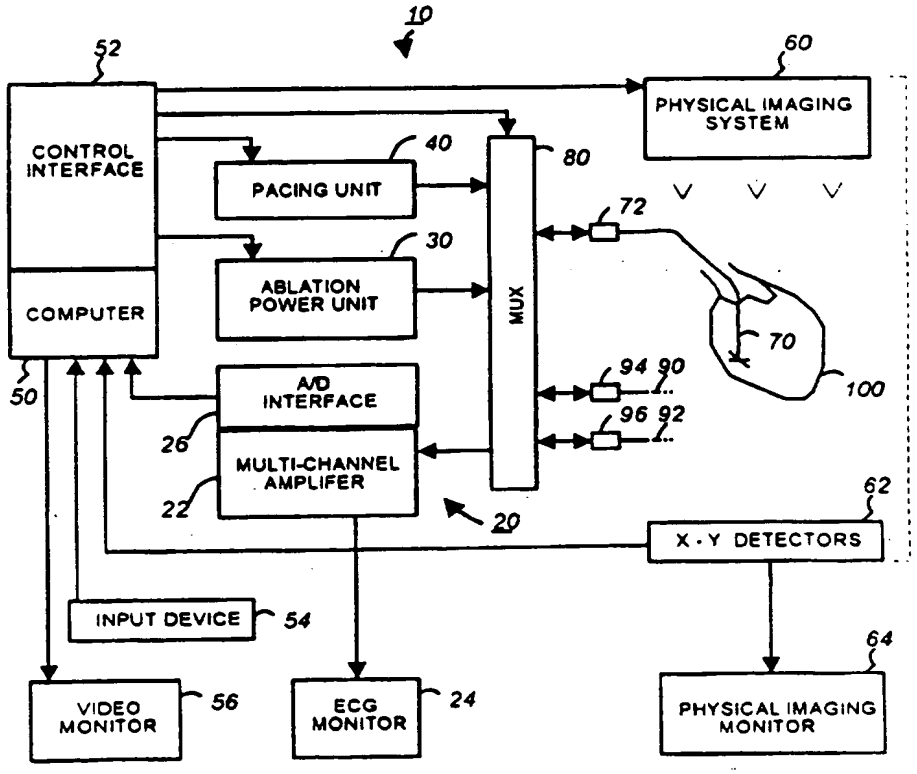
(54) Title: APPARATUS FOR CARDIAC ABLATION

(57) Abstract

A system and method for cardiac mapping and ablation include a multi-electrode catheter introduced percutaneously into a subject's heart and deployable adjacent to various endocardial sites. The electrodes are connectable to a mapping unit, an ablation power unit, a pacing unit, all of which are under computer control. Intracardiac electrogram signals emanated from a tachycardia site of origin are detectable by the electrodes. Their arrival times are processed to generate various visual maps to provide real-time guidance for steering the catheter to the tachycardia site of origin. In another aspect, the system also includes a physical imaging system which is capable of providing different imaged physical views of the catheter and the heart. These physical views are incorporated into the various visual maps to provide a more physical representation. Once the electrodes are on top of the tachycardia site of origin, electrical energy is supplied by the ablation power unit to effect ablation.



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APPARATUS FOR CARDIAC ABLATION

BACKGROUND OF THE INVENTION

This invention relates to medical devices and, in particular, a system and technique of employing multi-electrode catheters for cardiac mapping and ablation.

Cardiac dysrhythmias are commonly known as irregular heart beats or racing heart. Two such heart rhythm irregularities are the Wolff-Parkinson-White syndrome and atrioventricular (AV) nodal reentrant tachycardia. These conditions are caused by an extraneous strand of conducting fibers in the heart that provides an abnormal short-circuit pathway for electric impulses normally conducting in the heart. For example, in one type of Wolff-Parkinson-White syndrome the accessory pathway causes the electric impulses that normally travel from the upper to the lower chamber of the heart to be fed back to the upper chamber. Another common type of cardiac dysrhythmias is ventricular tachycardia (VT), which is a complication of a heart attack or reduction of blood supply to an area of heart muscle, and is a life threatening arrhythmia. All these types of dysrhythmias can usually be traced to one or more pathological "sites of origin" or tachycardia foci in the heart.

In the treatment of cardiac dysrhythmias, non-surgical procedures such as management with drugs are

favored. However, some dysrhythmias of the heart are not treatable with drugs. These patients are then treated with either surgical resection of the site of origin or by Automatic implantable cardiovertor defibrillator (AICD). Both procedures have increased morbidity and mortality and are extremely expensive. Even AICD needs major surgical intervention. In addition, some patients of advanced age or illness cannot tolerate invasive surgery to excise tachycardia focus which causes dysrhythmias.

Techniques have been developed to locate sites of tachycardia and to disable their short-circuit function. The site of origin of tachycardia is determined by analysis of surface electrocardiogram or intracardiac electrogram signals during states of arrhythmias which may occur spontaneously or be induced by programmed pacing. Once the site of origin or focus is located, the cardiac tissues around the site are either ablated surgically or with electrical energy so as to interrupt abnormal conduction.

For cardiac mapping, several methods of gathering and analyzing surface electrocardiogram or intracardiac electrogram signals are commonly used.

Surface electrocardiogram is one tool in which the electrocardiograms are gathered from as many as twelve surface electrodes attached to various external body parts of a subject. The ensemble of electrocardiograms usually has a definite signature which may be matched to that generally established to associate with a site of origin in a given location of the heart. In this way, it is possible to determine the gross location of a tachycardia site in the heart.

Intracardiac electrogram allows a tachycardia site of focus to be located more accurately. It is

obtained by detecting electrical signals within the heart by means of electrodes attached directly thereto.

Gallagher et al., "Techniques of Intraoperative ELectrophysiologic Mapping", The American Journal of Cardiology, volume 49, Jan. 1982, pp. 221-240, disclose and review several methods of intraoperative mapping in which the heart is exposed by surgery and electrodes are attached directly to it. In one technique, the electrodes at one end of a roving catheter are placed on a series of epicardial or endocardial sites to obtain electrograms for mapping earliest site of activation with reference to surface electrocardiograms. For endocardial mapping, a cardiotomy may also be necessary to open the heart to gain access to the endocardium.

Gallagher et al., supra, also disclose a technique for simultaneous, global mapping of the external surface of the heart (epicardial mapping). A lattice of about 100 electrodes in the form of a sock is worn on the heart, thereby enabling multiple sites to be recorded simultaneously. This technique is particular useful for those cases where the ventricular tachycardia induced is unstable or polymorphic.

Global mapping by means of large array of electrodes has been further disclosed in the following two journal articles: Louise Harris, M.D., et al., "Activation Sequence of Ventricular Tachycardia: Endocardial and Epicardial Mapping Studies in the Human Ventricle," Journal of American College of Cardiology (JACC), Vol. 10, November 1987, pp. 1040-1047; Eugene Downar, et al., "Intraoperative Electrical Ablation of Ventricular Arrhythmias: A "Closed Heart" Procedure," JACC, Vol. 10, No. 5, November 1987, pp. 1048-1056. For mapping the interior surface of the heart (endocardial mapping), a

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lattice of about 100 electrodes in the form of a inflatable balloon is placed inside the heart after cutting it open. Under some situations, a "closed heart" variation may be possible without the need for both a ventriculotomy and ventricular resection. For example, with the subject on cardiopulmonary bypass, a deflated balloon electrode array is introduced into the left ventricular cavity across the mitral valve. Once inside the ventricle, the balloon is inflated to have the electrodes thereon contacting the endocardium.

While the sock or balloon electrode arrays allow global mapping by acquiring electrogram signals over a wider area of the heart simultaneously, they can only be installed after open-chest surgery.

Catheter endocardial mapping is a technique for mapping the electrical signals inside the heart without the need for open-chest or open-heart surgery. It is a technique that typically involves percutaneously introducing an electrode catheter into the patient. The electrode catheter is passed through a blood vessel, like femoral vein or aorta and thence into an endocardial site such as the atrium or ventricle of the heart. A tachycardia is induced and a continuous, simultaneous recording made with a multichannel recorder while the electrode catheter is moved to different endocardial positions. When a tachycardia focus is located as indicated in intracardiac electrogram recordings, it is marked by means of a fluoroscope image. Catheter endocardial mapping are disclosed in the following papers:

M.E. Josephson and C.D. Gottlieb, et al., "Ventricular Tachycardias Associated with Coronary Artery Disease," Chapter 63, pp. 571-580, CARDIAC ELECTROPHYSIOLOGY - from cell to bedside, D.P Zipes et al,

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Editors, W.B. Saunders, Philadephia, 1990.

M. E. Josephson et al., "Role of Catheter Mapping in the Preoperative Evaluation of Ventricular Tachycardia," The American Journal of Cardiology, Vol. 49, January 1982, pp. 207-220. Linear multipolar electrode catheters are used in preoperative endocardial mapping.

F. Morady et al., "Catheter Ablation of Ventricular Tachycardia With Intracardiac Shocks: Results in 33 Patients," CIRCULATION, Vol. 75, No. 5, May 1987, pp. 1037-1049.

Kadish et al., "Vector Mapping of Myocardial Activation," CIRCULATION, Vol. 74, No. 3, September 1986, pp. 603-615.

U.S. Patent No. 4,940,064 to Desai discloses an orthogonal electrode catheter array (OECA). Desai et al., "Orthogonal Electrode Catheter Array for Mapping of Endocardiac Focal Site of Ventricular Activation," PACE, Vol. 14, April 1991, pp. 557-574. This journal article discloses the use of an orthogonal electrode catheter array for locating problem sites in a heart.

Upon locating a tachycardia focus, ablation of cardiac arrhythmias is typically performed by means of a standard electrode catheter. Electrical energy in the form of direct current or radiofrequency is used to create a lesion in the endocardiac tissues adjacent (i.e. underneath) the standard electrode catheter. By creating one or more lesions, the tachycardia focus may be turned into a region of necrotic tissue, thereby disabling any malfunctions.

Existing catheter mapping techniques typically rely on analysis of recorded electrograms. Locating the site of origin and tracking the whereabouts of the catheter are at best tricky and time-consuming, and often

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proved unsuccessful.

Thus, it is desirable, to have a catheter mapping and ablation system with precision and speed and able to provide comprehensive guidance on a real-time basis.

OBJECTS AND SUMMARY OF THE INVENTION

Accordingly, it is a general object of the present invention to treat ventricular tachycardia and other cardiac dysrhythmias by improved catheter mapping and ablations.

It is an object of the present invention to provide a system which is capable of rapid and accurate cardiac mapping.

It is another object of the present invention to provide a system which is capable of efficiently and accurately locating and ablating a site of origin of tachycardia.

It is another object of the present invention to provide accurate guidance for efficiently and accurately ablating an endocardial site by filling it with successive catheter ablations of a smaller area.

It is yet another object of the present invention to provide real-time visual maps indicating the relative positions of the electrodes, the tachycardia site of origin and the heart.

These and additional objects are accomplished by a system including a multi-electrode catheter selectively connectable to a mapping unit, an ablation unit and a pacing unit. The system also includes a computer for controlling the various functional components. In one embodiment the system additionally includes a physical imaging unit which is capable of providing different views

of a physical image of the multi-electrode catheter percutaneously introduced into the heart of a subject.

Electrogram signals emanated from a tachycardia site of origin in the endocardium are detectable by the electrode array. Their arrival times are processed to generate various visual maps to provide real-time guidance for steering the catheter to the tachycardia site of origin.

In one embodiment, the visual map includes a footprint of the electrode array on an endocardial site. The arrival time registered at each electrode is displayed in association therewith. A medical practitioner can therefore steer the catheter in the direction of earlier and earlier arrival time until the tachycardia site of origin is located.

In another embodiment, the visual map also includes isochrones which are contours of equal arrival time. These isochrones are constructed by linear interpolation of arrival times registered at the electrode array and cover the area spanned by the electrode array. When the electrode array is far from the tachycardia site of origin, the isochrones are characterized by parallel contours. When the electrode array is close to or on top of the tachycardia site of origin, the isochrones are characterized by elliptical contours encircling the tachycardia site of origin. Therefore, the isochrones provide additional visual aid and confirmation for steering the catheter to the tachycardia site of origin.

In another preferred embodiment, the visual map also includes an estimated location of the tachycardia site of origin relative to the electrode array. This provides direct visual guidance for rapidly steering the catheter to the tachycardia site of origin. The

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tachycardia site of origin lies in the weighed direction of electrodes with the earliest arrival times. The distance is computed from the velocity and time of flight between the site of origin and a central electrode. The velocity is estimated from a local velocity computed from the inter-electrode spacings and arrival time differentials.

According to another aspect of the invention, the system also include a physical imaging system which is capable of providing different imaged physical views of the catheter and the heart. These physical views are incorporated into the various visual maps to provide a more physical representation.

In one embodiment, two visual maps display two views (e.g., x,y axes) of a physical image of the electrode array in the heart with a relative position for the tachycardia site of origin.

In another embodiment, a visual map display a three-dimensional perspective view of the electrode array in the heart with a relative position for the tachycardia site of origin.

In yet another embodiment, the visual map also marks previous sites or tracks visited by the electrode array.

With the aid of the visual maps, the electrode array can locate the tachycardia site of origin rapidly and accurately. The system then directs electrical energy from the ablation power unit to the electrode array to effect ablation.

Additional objects, features and advantages of the present invention will be understood from the following description of the preferred embodiments, which

description should be taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic block diagram of a multi-electrode catheter mapping and ablation system of the invention;

Figure 2A illustrates the proximal end of the orthogonal electrode catheter array (OECA) in its fully retracted position or mode;

Figure 2B illustrates the OECA in its fanned-out mode;

Figure 2C shows the footprints of the five-electrode OECA electrodes;

Figure 3A illustrates the five electrodes of the OCEA positioned on a pair of orthogonal axes, each passing through a pair of peripheral electrodes and the central electrode;

Figure 3B shows an example measurement of the OECA from one endocardial site;

Figure 3C illustrates the linear interpolation scheme applied to Quadrant I of the example shown in Figure 3B;

Figure 3D shows the construction of a complete local isochronal map for the entire area cover by the OECA as shown in Figure 3D;

Figure 4 shows example traces of surface EKG and intracardiac electrogram;

Figure 5 illustrates schematically the ventricle or other heart chamber divided arbitrarily into four segments, and the isochrone maps obtained from various locations;

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Figure 6A illustrates by an example the construction of the displacement vector of the electrode array to the estimated site of origin;

Figure 6B is a display on the video monitor showing the relative positions of the electrode array and the estimated site of origin, according to a preferred embodiment of the invention;

Figure 6C illustrates a display according to another embodiment which includes the electrode array with the arrival times and the local isochrone map;

Figure 7A is a synthesized display on the video monitor of a digitized picture of the heart and the electrode array therein taken along a first axis by the physical imaging system, and also showing the relative position of the estimated site of origin, according to another preferred embodiment of the invention;

Figure 7B is a display on the video monitor showing a similar picture as in Figure 7A but taken along a second axis by the physical imaging system;

Figure 8 is a display on the video monitor showing the pictures of Figure 7A and 7B simultaneously, according to another preferred embodiment of the invention;

Figure 9 is a display on the video monitor showing a relative position of the estimated site of origin against a perspective picture of the heart and the electrode array which is synthesized from pictures recorded from along several axes by the physical imaging system, according to another preferred embodiment of the invention;

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 is a schematic block diagram of a multi-electrode catheter mapping and ablation system 10 according to a preferred embodiment of the present invention.

The system 10 essentially comprises of three functioning units, namely a mapping unit 20, an ablation unit 30 and a pacing unit 40. A computer 50 controls the operation of each of the units and their cooperations via a control interface 52. The computer receives operator inputs from an input device 54 such as a keyboard, a mouse and a control panel. The output of the computer may be displayed on a video monitor 56 or other output devices (not shown).

In the preferred embodiment the system 10 also includes a physical imaging system 60. The physical imaging system 60 is preferably a 2-axis fluoroscope or an ultrasonic imaging system. The physical imaging system 60 is controllable by the computer 50 via the control interface 52. In one implementation, the computer triggers the physical imaging system to take "snap-shot" pictures of the heart 100 of a patient (body not shown). The picture image is detected by a detector 62 along each axis of imaging. It usually includes a silhouette of the heart as well as inserted catheters and electrodes, and is displayed by a physical imaging monitor 64. Two monitors may be used to display the two images obtained along each of the dual axes. Alternatively, the two images may be displayed side-by-side on the same monitor. A digitized image data is also fed into the computer 50 for processing and integrating into computer graphics to be displayed on the video monitor 56.

A multi-electrode catheter 70 is selectively routed to each of the three functioning units 20, 30 and 40 via a catheter lead connector 72 to a multiplexor 80. Auxiliary catheters 90 or electrodes 92 are also connectable to the multiplexor 80 via one or more additional connectors such as 94, 96.

During cardial procedures, the multi-electrode catheter 70 is typically introduced percutaneously into the heart 100. The catheter is passed through a blood vessel (not shown), like femoral vein or aorta and thence into an endocardial site such as the atrium or ventricle of the heart. Similarly, auxiliary catheters 90 may also be introduced into the heart and/or additional surface electrodes 92 attached to the skin of the patient.

When the system 10 is operating in a mapping mode, the multi-electrode catheter 70 as well as optional auxiliary catheters 90 function as detectors of intra-electrocardiac signals. The surface electrodes 92 serve as detectors of surface electrocardiogram signals. The analog signals obtained from these multi-electrode catheters and surface electrodes are routed by the multiplexor 80 to a multi-channel amplifier 22. The amplified signals are displayable by an electrocardiogram (EKG) monitor 24. The analog signals are also digitized via an A/D interface 26 and input into the computer 50 for data processing and graphical display. Further details of the data acquisition, analysis, and display relating to intracardiac mapping will be disclosed later.

When the system 10 is operating in an ablation mode, the multi-electrode catheter 70 is energized by the ablation unit 30 under the control of the computer 50. An operator issues a command through the input device 54 to the computer 50. The computer controls the ablation unit

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30 through the control interface 52. This initiates a programmed series of electrical energy pulses to the endocardium via the catheter 70. A preferred implementation of the ablation method and device is disclosed in U.S. Patent No. 5,383,917 by Desai, et al., the entire disclosure thereof is incorporated herein by reference.

When the system 10 is operating in a pacing mode, the multi-electrode catheter 70 is energized by the pacing unit 40 under the control of the computer 50. An operator issues a command through the input device 54 whereby the computer 50 controls through the control interface 52 and multiplexor 80 and initiates a programmed series of electrical simulating pulses to the endocardium via the catheter 70 or one of the auxiliary catheters 90. A preferred implementation of the pacing mode is disclosed in M. E. Josephson et al., "VENTRICULAR ENDOCARDIAL PACING II. The Role of Pace Mapping to Localize Origin of Ventricular Tachycardia," The American Journal of Cardiology, Vol. 50, November 1982, relevant portion of the disclosure thereof is incorporated herein by reference.

In an alternative embodiment, the ablation unit 30 is not controlled by the computer 50 and is operated manually directly under operator control. Similarly, the pacing unit 40 may also be operated manually directly under operator control. The connections of the various components of the system 10 to the catheter 70, the auxiliary catheters 90 or surface electrodes 92 may also be switched manually via the multiplexor 80.

MAPPING

An important advantage of the present invention is the capability of allowing a medical practitioner to use a roving catheter to locate the site of origin of tachycardia in the endocardium quickly and accurately, without the need for open-chest and open-heart surgery. This is accomplished by the use of the multi-electrode catheter 70 in combination with real-time data-processing and interactive display by the system 10.

Essentially, the multi-electrode catheter 70 must be able to deploy at least a two-dimensional array of electrodes against a site of the endocardium to be mapped. The intracardiac signals detected by each of the electrodes provide data sampling of the electrical activity in the local site spanned by the array of electrodes. This data is processed by the computer to produce a real-time display including arrival times of intracardiac signals at each electrode, and a local isochrone map of the sampled site. By plotting contours of equal arrival time of the intracardiac signals, the local isochrone map is an expedient way of indicating how close and where the electrode array is from the site of origin. Also, at each sampled site, the computer computes and displays in real-time an estimated location of the site of origin relative to the electrodes, so that a medical practitioner can interactively and quickly move the electrodes towards the site of origin.

A suitable multi-electrode catheter for use in the present invention is a five-electrode orthogonal electrode catheter array (OECA) that has been disclosed in U.S. Patent No. 4,940,064 to Desai. Relevant portions of said disclosure are incorporated herein by reference.

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Figure 2A illustrates the proximal end of the orthogonal electrode catheter array (OECA) 70 in its fully retracted position or mode. Because the catheter material has a "set" or "memory" it will normally return to this retracted position. The OECA comprises an eight-french five-pole electrode catheter 70. It has a central stylet 102 with four peripheral or circumferential electrodes 112, 113, 114 and 115. A fifth electrode 111 is located centrally at the tip of the stylet 102. All five electrodes are hemispherical and have individual leads 116 connected thereto. Each peripheral electrode is 2 mm in diameter while the central electrode is 2.7 mm in diameter. Slits 120 are cut longitudinally near where the electrodes are located.

Figure 2B illustrates the OECA in its fanned-out mode. When the proximal end (not shown) of the catheter is pulled, the stylet's slits 120 allow four side arms 122 to open from the stylet body in an orthogonal configuration. Each of the four arms 122 extend a peripheral electrode radially from the stylet so that the four peripheral electrodes forms a cross with the fifth electrode 111 at its center. The inter-electrode distance from the central electrode to each peripheral electrode is 0.5 cm, and the distance between peripheral electrodes is 0.7 cm. The surface area of the catheter tip in an open position is 0.8 cm^2.

Figure 2C shows the footprints of the five-electrode OECA electrodes. The four peripheral electrodes 112, 113, 114 and 115 or (2)-(5) form a cross configuration. The fifth electrode 111 or (1) is located at the center of the cross. The orthogonal array of electrodes therefore provides five sampling points over

the zone 130 in an endocardium site spanned by the electrodes.

ISOCHRONE MAPS

Generally when a patient's heart is in a state of tachycardia, the site of origin becomes the source of endocardial activation, emanating a series of activation wavefronts therefrom. Electrodes such as those deployed by the catheter 70 in the endocardium and located closer to the site of origin will detect these wavefronts earlier than those further away. The surface electrodes 92 being the furthest away from the site of origin will generally register latest wavefront arrival times.

When an endocardial site is being mapped by the OECA, a single measurement of an activation wavefront will provide arrival times at the five electrodes in real time. A local isochrone map for the sampled site can then be constructed from these arrival times, thereby showing contours of equal arrival times. The isochrones are readily computed by the computer using a linear interpolation scheme, as illustrated below.

Figure 3A illustrates the five electrodes of the OCEA positioned on a pair of orthogonal axes. Each orthogonal axes passes through a pair of peripheral electrodes and the central electrode, viz 112-111-114 (or (2)-(1)-(4)) and 113-111-115 (or (3)-(1)-(5)). To implement the linear interpolation scheme, the zone spanned by the five electrodes is best divided into four triangular quadrants I to IV. Quadrant I is bounded by electrodes (1), (2), and (3). Quadrant II is bounded by electrodes (1), (3), and (4). Quadrant III is bounded by electrodes (1), (4), and (5). Quadrant IV is bounded by electrodes (1), (5), and (2). The local isochrones are

then computed for each quadrant separately using linear interpolation along each side of the triangle.

Figure 3B shows an example measurement of the OECA taken from one endocardial site. The five electrodes [(1), (2), (3), (4), (5)] each respectively has arrival time of [t(1), t(2), t(3), t(4), t(5)] = [-16, -6, -8, -20, -14] msec.

Figure 3C illustrates the linear interpolation scheme applied to Quadrant I of the example shown in Figure 3B. Quadrant I is a triangle defined by the electrodes [(1), (2), (3)], each respectively having arrival times of [t(1), t(2), t(3)] = [-16, -6, -8] msec. Taking one millisecond steps, the side defined by electrodes (1) and (2) can be divided into ten equal steps from t = -6 to -16 msec. Similarly, the side defined by electrodes (2) and (3) can be divided into two equal steps from t = -6 to -8 msec, and the side defined by electrodes (1) and (3) can be divided into eight equal steps from t = -8 to -16 msec. Thus, an isochrone for the arrival time of -10 milliseconds can easily be drawn by joining a line from the -10 msec coordinate along each side. In this instance, the -10 msec coordinate is found only along the two sides defined by electrodes (1) and (2) and electrodes (1) and (3).

Figure 3D shows the construction of a complete local isochronal map for the entire area covered by the OECA. The complete local isochronal map is obtained by applying the linear interpolation method to all quadrants for all desired arrival times.

The activation wavefront arrival time at each electrode is measured relative to a reference time. The reference time is usually provided by the earliest deflection in a surface electrocardiogram which is

monitored throughout the cardiac procedure.

Figure 4 shows typical example traces of surface EKG and intracardiac electrograms. The top three traces are three surface electrocardiograms I, AVF and V1, representing three planes (right to left, superior-inferior, anterior-posterior). These are continuously monitored and the earliest deflection on any of these electrocardiograms serves as a reference point of time. In this example, a perpendicular dotted line (reference time zero) is drawn from the earliest surface EKG which happens to be lead I. The next five traces are unipolar intracardiac electrograms as detected by an orthogonal electrode array catheter. It can been seen that electrode number 5, having the earliest arrival time of -36 msec is closer to the site of origin than the others.

It has been determined that an arrival time of -40 to -45 msec indicates that the detecting electrode is located substantially at the site of origin. In this case, the OECA yields a local isochrone map characterized by elliptical contours centered on the central electrode. On the other hand, when the OECA is substantially far away from the site of origin, its local isochrone map is characterized by parallel contours. The characteristic arrival time and associated isochronal signature are useful for locating the site of origin.

The intracardiac and surface EKGs are preferably digitized using a simple 8 or 16 channel signal digitizer. When the system 10 is in the mapping mode, the intracardiac electrograms and surface EKGs obtained from the multi-electrode catheter 70 and the surface electrodes 92 are digitized by the A/D interface 26. The digitized waveforms are analyzed by the computer to find the activation wavefront arrival times in real time.

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The method of operation of the inventive system in mapping mode will now be described by way of an example as follows. The multi-electrode catheter 70 is first used in mapping. The catheter is inserted through the leg artery (right femoral) and advanced to the aortic arch and then to the left ventricle utilizing fluoroscopic guidance as provided by the physical imaging system 60.

Figure 5 illustrates schematically the ventricle or other heart chamber divided arbitrarily into four segments, right-upper (RUS) and right-lower (RLS), and left-upper (LUS) and left-lower (LLS) segments. In the example shown, a site of origin 200 is located in the (LLS) segment. The catheter 70 (OECA) is used to sample each of the segments in order to identify the segment containing the site of origin 200. The OECA is first positioned in the right upper segment, and its orthogonal electrode array is deployed to measure arrival times of wavefront activation from the site of origin. The system 10 is then instructed to initiate tachycardia by means of programmed electrical stimulation protocol from the pacing unit 40 to an electrode inserted into the endocardium. Once tachycardia is induced, the OECA picks up the intracardiac activation wavefront arrival times which are analyzed by the computer and a local isochrone map is displayed on the video monitor 56. In the example shown in fig. 5, when the OECA is in the (RUS) segment, all electrodes register a rather late arrival time, which indicates that the site of origin is not in the (RUS) segment.

Next, the catheter electrodes are retracted and the catheter moved to the lower segment (RLS). In this way all four segments are mapped. In the example shown,

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the catheter is eventually repositioned in the segment (e.g., LLS) that demonstrates earliest arrival times.

Once the segment containing the site of origin has been identified, further manipulations of the catheter in that segment are undertaken with the interactive aid of the display on the video monitor 56. The display shows in real-time the local isochrone map, the electrode array and the estimated position of the site of origin relative thereto.

Figure 6A illustrates by an example the construction of the displacement vector of the electrode array to the estimated site of origin 201. Shown in Figure 6A are the five electrodes of the OECA which are identical to the ones shown in Figure 3A. The example shown has the five electrodes [(1), (2), (3), (4), (5)] each detecting an activation wavefront arrival time respectively of [t(1), t(2), t(3), t(4), t(5)] = [-36, -27, -32, -40, -31] msec. The orthogonal interelectrode spacing is R = 5mm in this case. As explained before, the goal is to locate the electrode array centrally about the actual site of origin. Since the site of origin is the source of the activation wavefronts an electrode located at the site will detect the earliest possible arrival time (typically -40 to 44msec with respect to the first deflection of the surface EKG). The goal is achieved by having the central electrode (1) detecting the earliest possible arrival time. Conversely, when the electrode array is displaced from the site of origin, those electrodes further away from the site of origin will detect arrival times later (less negative) than those that are closer (more negative). Thus, the electrode array must be moved along the direction of more negative arrival time in order to close in on the site of origin.

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According to one embodiment, the direction in which the displacement vector joining the center of the electrode array to the estimated site of origin 201 is determined by linear interpolation of the respective arrival times detected at the five electrode locations. This can be easily performed by treating each arrival time as an "equivalent mass" located at each electrode and calculating the "center of mass" for the electrode array. The position of the "center of mass" is then given by:

$$[R_x, R_y] = \left[\frac{\sum_i r_x(i) t_x(i)}{\sum_i t_x(i)}, \frac{\sum_j r_y(j) t_y(j)}{\sum_j t_y(j)} \right] \quad (1)$$

The OECA conveniently defines a set of orthogonal axes with an (x,y) coordinate system, viz: the direction along electrodes (1)-(2) being the y-axis and the direction along electrodes (1)-(3) being the x-axis. The example data yield the position of the "center of mass" relative to the electrode (1):

$$[R_x, R_y] = \left[\frac{-32 * R + (-31) * (-R)}{-32 + (-31)}, \frac{-27 * R + (-40) * (-R)}{-27 + (-40)} \right] \quad (2)$$

$$= [0.016, -0.19] R$$

where R = orthogonal interelectrode spacing (e.g. =5mm).

The estimated site of origin 201 then lies along a direction D^ defined by a line through the central electrode (1) and the "center of mass", $[R_x, R_y]$.

According to one aspect of the invention, the distance, |D|, between the central electrode (1) and the

$$|D| = v_D |t(f) - t(1)| \quad (3)$$

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site of origin is estimated by first determining the local wavefront velocity, v_D, along the direction D^. Thus, where

t(f) = arrival time measured at the site of origin,

t(1) = arrival time measured at the central electrode (1).

In the case of the OECA, it is expediently accomplished by first computing the wavefront velocities along the x- and y-axis. This is estimated by the speed the wavefront travel from one electrode to another along the x- and y-axis:

$$[v_x, v_y] = \left[\frac{R}{\Delta t_x}, \frac{R}{\Delta t_y}\right] \qquad (4)$$

where R = interelectrode spacing, and the appropriate Δt_x, Δt_y are given by the table below corresponding to the quadrant containing the direction D^:

QUADRANT	Δt_x	Δt_y
(1)-(2)-(3)	t(1)-t(3)	t(1)-t(2)
(1)-(3)-(4)	t(1)-t(3)	t(1)-t(4)
(1)-(4)-(5)	t(1)-t(5)	t(1)-t(4)
(1)-(2)-(5)	t(1)-t(5)	t(1)-t(2)

The local wavefront velocity v_D is estimated by adding the component of v_x and v_y along the direction D^, viz.:

$$v_D = v_x \cos\theta + v_y \sin\theta \qquad (5)$$

where $\theta = \tan^{-1}(R_x/R_y)$ is the angle between D^ and the x-axis.

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In the example given in Figure 6A, the direction D^ lies within the quadrant (1)-(3)-(4). Then Equation (4) yields

$$[v_x, v_y] = [\frac{1}{-4}, \frac{1}{4}]R/ms$$

and Equation (5) yields

$$v_D = 0.25R(-\cos\theta + \sin\theta)/msec \approx -0.25R/msec.$$

If the site of origin is assumed to have a measured arrival time of t(f)=-44 msec, then from Equation (3) the central electrode is displaced from the estimated site of origin 201 by a distance:

$$D = v_D(44-36) = 2R \text{ or } 10mm.$$

Figure 6B illustrates a computer graphical display on the video monitor 56 (see Figure 1) in the preferred embodiment. The display shows, in real time and simultaneously, the electrode array with its local isochrone map and the relative position of the estimated site of origin 201. This greatly facilitates a medical practitioner to quickly steer the electrode catheter array to the site of origin. As the electrode catheter array is moved towards the estimated site of origin 201, the isochrones should be more and more elliptical. When the central electrode 111 is on top of the estimated site of origin, the isochrones should be ellipes wrapping around the central electrode 111. If this is not the case, t(f) needs to be revised and preferably changed in steps of 2 msec at a time, until the event when coincidence of the central electrode with the estimated site of origin is

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accompanied by elliptical isochrones wrapping around the central electrode.

As described earlier, Equation (1) is a linear interpolation scheme based on repesresenting the arrival time at each electrode with an equivalent mass; the

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earlier the arrival time, the more "massive" it is. In this way, the data collected by every electrode in the array is taken into consideration. The equation as it stands is applicable if all the arrival time is negative, which is the case when the electrodes are not too far off-field from the site of origin. In general, to accommodate also positive or mixed positive and negative values of arrival times, it is expedient to shift all the arrival time values to the same polarity with the view of having the earliest arrival time represented by the largest value. In one embodiment, the arrival times are translated by the formulae

$$t_x \rightarrow T_0 - t_x$$
$$t_y \rightarrow T_0 - t_y$$

where T_0 is a positive constant larger than any of the positive arrival time values. For example, $T_0 = 50$, and the calculation in Equation (2) yields $[R_x, R_y] \approx [1, -13]R$.

Figure 6C illustrates a display according to another embodiment which includes the electrode array with the arrival times and the local isochrone map. In this embodiment, an arrow 313 indicates the estimated direction in which the catheter array should move in order to approach the site of origin. In general, as the catheter array is moved from site to site, there will be a map such as that illustrated in Fig. 6c associated with each site, with the current display showing the reading from the current site.

A further feature is the ability to store maps from previous sites and to recall these "history" information as needed. In one embodiment, another arrow 311 associated with the previous site is also displayed on the current map to provide a line of reference from the previous site. The previous arrow is displayed with a

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different attribute such as with broken line or with a different color in order to distinguish over the present arrow. In this way, the operator maneuvering the catheter will be able to tell whether the current catheter position is getting closer to the site of origin relative to the last one. In another embodiment, the previous map is display in a smaller window in one corner of the current map.

In yet another embodiment, as the catheter is mapping from site to site, the operator is able to mark the sites interactively on a graphical terminal. Typically, on the graphical terminal is displayed a schematic diagram of the heart such as the one shown in Fig. 5, and by reference to a flouoscopic image of the catheter in the heart, an operator can mark the equivalent site on the schematic diagram. Each marker on the schematic diagram is linked to its associated map or associated information. Subsequently, the operator is able to point to any existing marker and recall its associated map or information.

PHYSICAL IMAGE INTEGRATION

The computer video display shown in Figure 6B is constructed essentially from information obtained through data processing of wavefront arrival-time data sampled by the electrode catheter array 70. The display is an arrival-time field that exists in a two-dimensional space on the surface of the endocardium. For the purpose of locating the catheter at the site of origin, it provides adequate and cost-effective guidance.

According to another aspect of the invention, the information obtained by the physical imaging system 60

(see Figure 1) is also integrated with the information obtained from the wavefront arrival-time data. The two types of information are synthesized by the computer 50, and are displayed on the video monitor 56 as a physical image of the heart 100 and showing therein the relative positions of the electrode catheter array 70 and the estimated site of origin 201. In this way a more physical representation of the catheter and heart is possible.

Figure 7A is a synthesized display on the video monitor of a digitized picture of the heart 100 and the electrode array 70 therein taken along a first axis by the physical imaging system, and also showing the relative position of the estimated site of origin 201, according to another preferred embodiment of the invention.

In one implementation, the physical imaging system 60 (also see Figure 1) comprises two x-rays taken from two perpendicular directions. The video output of both x-ray machines is digitized, e.g., by using two separate video frame grabbers integrated into the x-y detectors 62. Since the electrode array 70 such as the OECA (also see Figures 2 and 3) has an x-ray opaque dart (not shown) on one of the electrode arms, it is relatively simple for the computer to properly identify each electrode and associate the correct arrival time with each electrode. In this way, the positions of the five electrodes of the OECA can be tracked by the computer 50 in real time.

The estimated site of origin 201 can be located by the method described earlier, except the coordinate system may be non-orthogonal, depending on the orientation of the electrode array.

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Figure 7B is a display on the video monitor showing a similar picture as in Figure 7A but taken along a second axis by the physical imaging system.

The views from the two axes may be displayed on two separated video monitors or on one monitor.

Figure 8 is a display on the video monitor showing the pictures of Figure 7A and 7B simultaneously, according to another preferred embodiment of the invention.

According to another embodiment of the invention, the video display is a perspective rendering of a three-dimensional image of the heart and the electrode array.

Figure 9 is a synthesized display on the video monitor of a perspective picture of the heart 100 and the electrode array 70 together with the estimated site of origin 201, according to another preferred embodiment of the invention. The image of heart 100 and the electrode array 70 are rendered from a three-dimensional image database which is collected from imaging along several axes by the physical imaging system. Each axis provide a view of the heart and the electrode array. The procedure for locating the estimated site of origin in each view is similar to that described before. The data gathered from the different views are processed by the computer to generate a three-dimensional perspective view. In one implementation, sites previously visited by the catheter 70 are also displayed as a track 211 in the endocardium.

The present inventive system is advantageous in allowing a medical practitioner to graphically track in real time the relative positions of the electrode array with respect to the heart and the estimated site of origin. Furthermore, it allows the possibility of accurate catheter positioning and repositioning in the

endocardium and the possibility of tracking the history of the catheter previous positions.

GLOBAL MAPPING

In preoperative studies and diagnosis or in medical research, a global mapping of the heart is valuable. A global isochronal map for the entire endocardium is assembled by the catheter scanning over the entire endocardium and the computer piecing together the local isochrone maps at each scanned site. The display includes tracks traversed by the catheter to provide guidance so that the endocardium can be mapped systematically. This will not only allow the computer to produce and display local isochronal maps in real time, but also separate isochronal maps of a larger area up to the whole endocardium by storing the actual positions of the electrodes for each measurement and the corresponding arrival times. As each additional measurement is taken, the (non-local) isochronal map could be updated to cover a larger area more accurately. This would allow the medical practitioner conducting a medical procedure to determine where to place the OECA next for measurement and to decide whether or not accurate enough isochronal map for the entire endocardium has been produced. Once an accurate enough isochronal map of the activation wavefront has been produced, a proper treatment procedure could then be determined.

MULTI-PHASE RADIO FREQUENCY ABLATION

A preferred implementation of the ablation method and device is disclosed in copending and commonly assigned U.S. patent application No. 07/762,035 filed July 5, 1991

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by Desai, et al., the entire disclosure thereof is incorporated herein by reference.

After the site of origin is located by the electrode array, the system 10 (Figure 1) is switched to the ablation mode. Electrical energy is transmitted from the ablation power unit 30 through the multiplexor 80 to the electrode array catheter 70. In the preferred embodiment, the ablation power unit 30 is programmable and under the control of the computer 50, so that a predetermined amount of electrical energy is delivered to ablate the endocardium.

In catheter ablation, the lesion formed is about the size of the energized electrode or electrode array. Conventional catheter ablation techniques have typically employed a catheter with a single electrode at its tip as one electrical pole. The other electrical pole is formed by a backplate in contact with a patient's external body part. These techniques have been used to disable the tachycardia site of origin in most cases. For example, it has been successfully used for the interruption or modification of conduction across the atrioventricular (AV) junction in AV nodal reentrant tachycardia; or for the interruption of accessory pathway in patients with tachycardia due to Wolff-Parkinson-White Syndrome; and for ablation in some patients with ventricular tachycardia (VT).

However, in ventricular tachycardia (VT), endocardial mapping with a standard electrode catheter can locate the exit site of ventricular tachycardia to within 4-8 cm^2 of the earliest site recorded by the catheter. A standard electrode catheter typically has a maximum electrode tip area of about 0.3 mm^2. Therefore, the lesion created by the simple RF technique delivered through a

standard electrode catheter may not be large enough to ablate the ventricular tachycardia. Attempts to increase the size of lesion by regulation of power and duration by increasing the size of electrode or by regulating the temperature of tip electrode have met with partial success.

In order to increase the size of the lesion, the orthogonal electrode catheter array (OECA) with four peripheral electrodes and one central electrode provides a larger footprint. It typically produces a lesions of 1 cm^2.

However, in the ablative treatment of ventricular tachycardia (VT), lesion size of the order of more than one cm^2 is probably required for effective treatment. In this case, a large lesion is formed by successive ablation of adjacent sites. For example, a larger lesion of 6 cm^2 size can be created by six adjacent square-shaped lesions of 1 cm^2. They can be formed by successive placements of the five-electrode OECA using RF energy. After each ablation, the electrode catheters is usually withdrawn to clean blood coagulum on the electrodes before the next attempt. It is critical that the locations of the next spot to be ablated as well as the reintroduced catheter must be known accurately and quickly for this procedure to be successful. This is accomplished by switching the system 10 alternately between the mapping and ablation mode. In the mapping mode, the system is preferably programmed to superposition a grid about the displayed tachycardia site such as that shown in Figs. 7, 8 or 9. The grid will enable accurate positioning of the electrode array.

While the embodiments of the various aspects of the present invention that have been described are the

preferred implementation, those skilled in the art will understand that variation thereof may also be possible. The device and method described therein are applicable to ablation of biological tissues in general. Therefore, the invention is entitled to protection within the full scope of the appended claims.

BNSDOCID: <WO 9632885A1>

IT IS CLAIMED:

1. A cardiac mapping system for locating a tachycardia site of origin in an endocardium of a subject's heart, comprising:

catheter means for disposing a cluster of electrodes about the endocardium site-by-site, each electrode capable of detecting intracardiac electrogram signals emanating from the tachycardia site of origin;

means responsive to the intracardiac electrogram signals detected at each electrode for computing an arrival time of the intracardiac electrogram signals thereat;

means for interactively displaying a map derived from said arrival times of intracardiac electrogram signals, said map including the cluster of electrodes and a display of arrival time associated with each electrode, whereby those electrodes being closer to the tachycardia site of origin than others will register earlier arrival times than others, and electrodes that are substantially coincident with the tachycardia site of origin will register an earliest possible arrival time, thereby said map providing guidance for moving said catheter in the direction of those electrodes having earlier arrival times; and

means for storing and displaying a map obtained from a previous site.

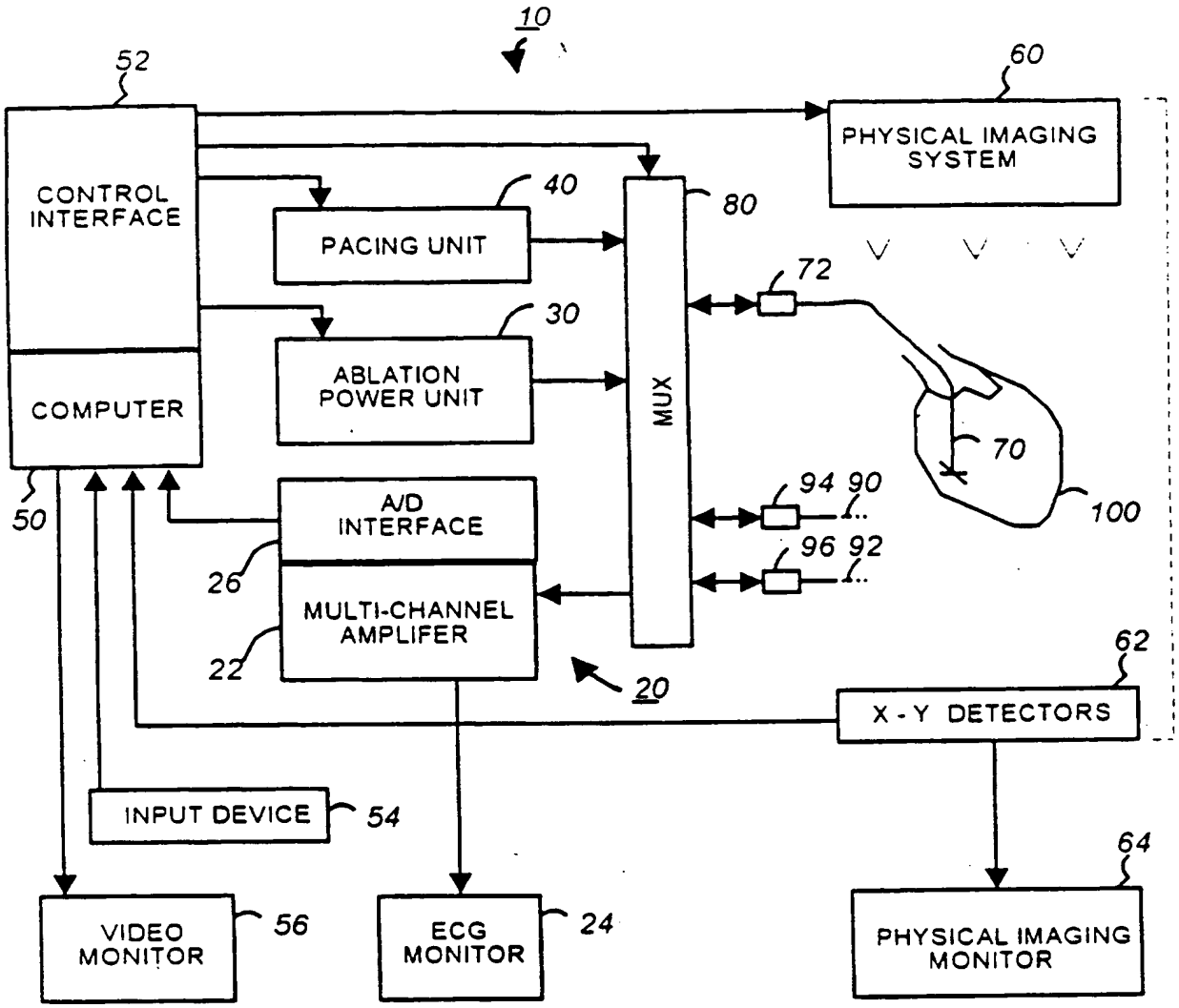

FIG. 1

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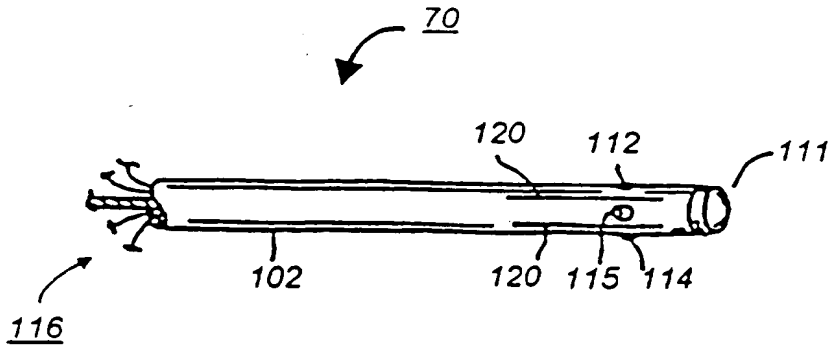

FIG. 2A

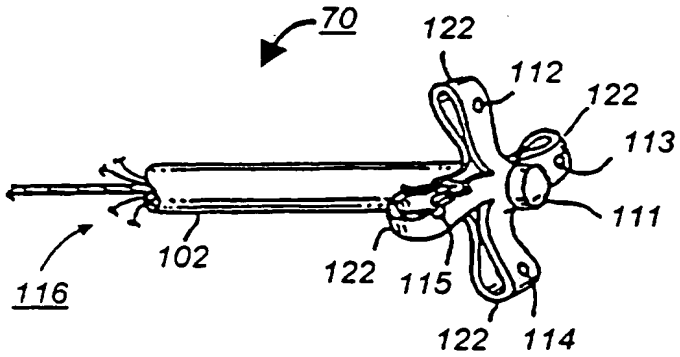

FIG. 2B

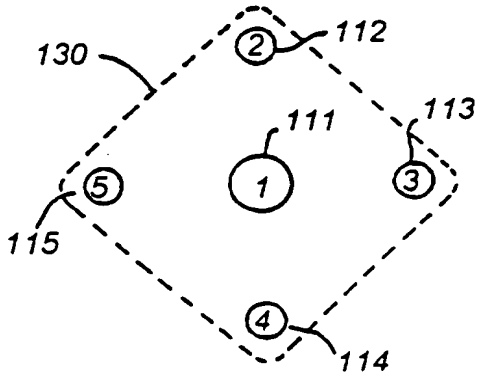

FIG. 2C

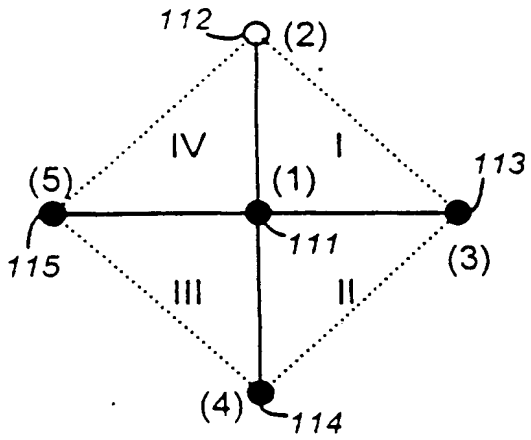

FIG. 3A

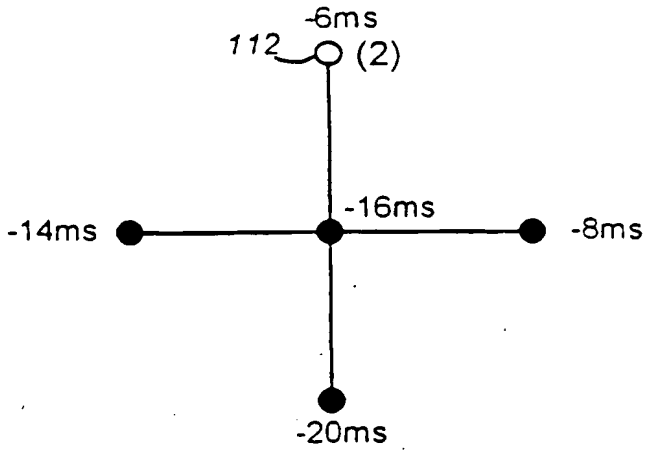

FIG. 3B

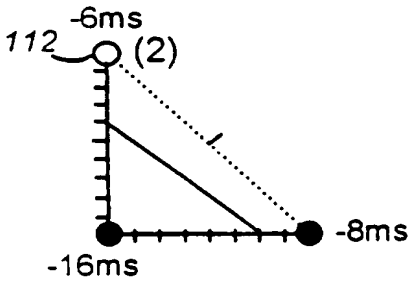

FIG. 3C

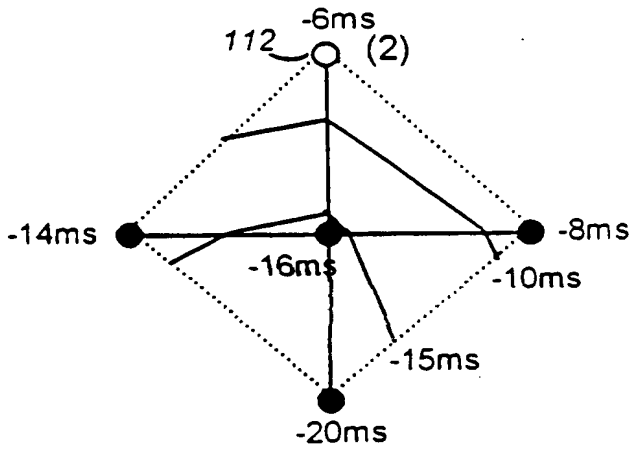

FIG. 3D

INSDOCID: <WO 9632885A1>

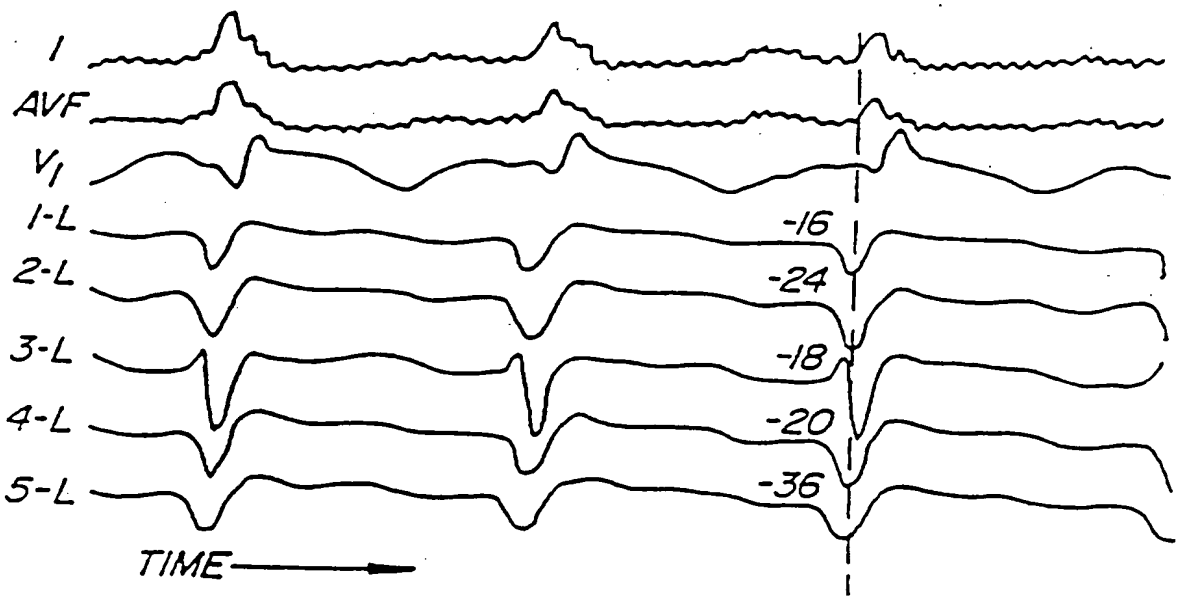

FIG. 4

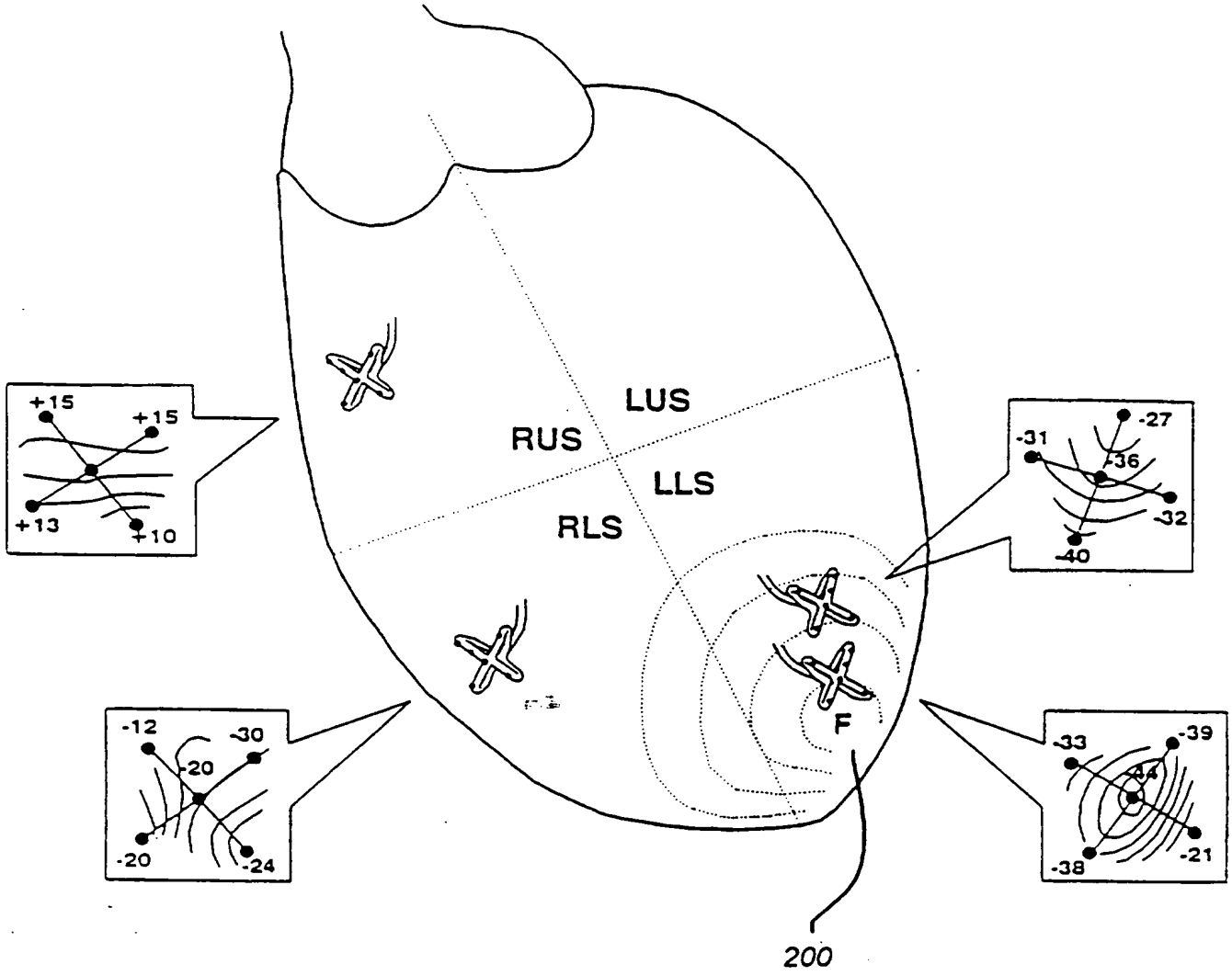

FIG. 5

BNSDOCID: <WO 9632885A1>

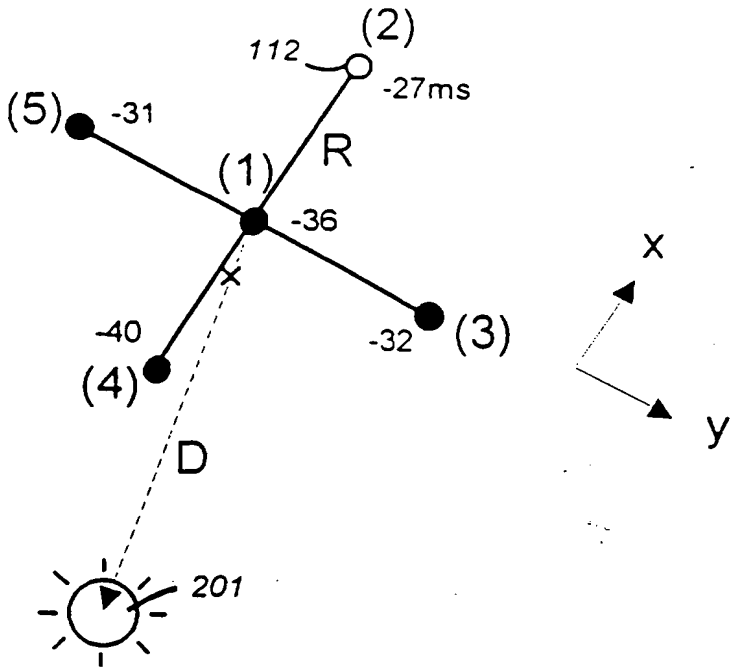

FIG. 6A

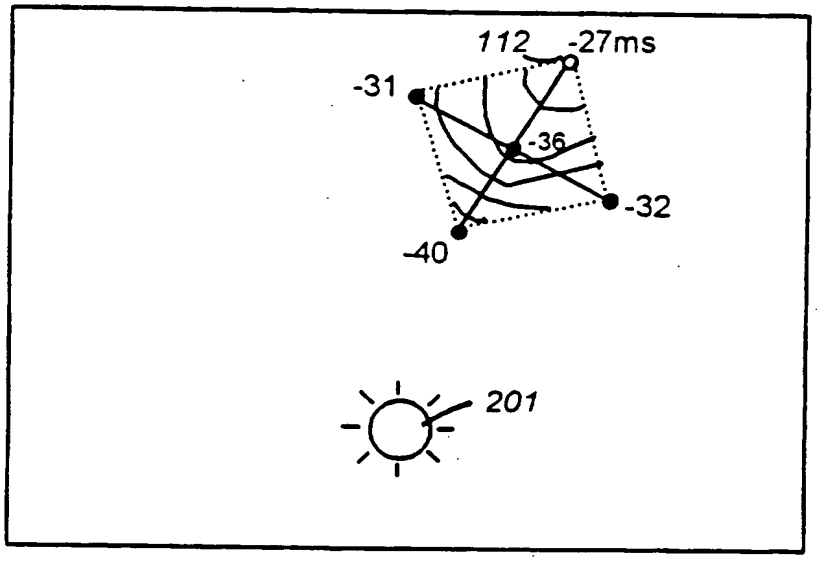

FIG. 6B

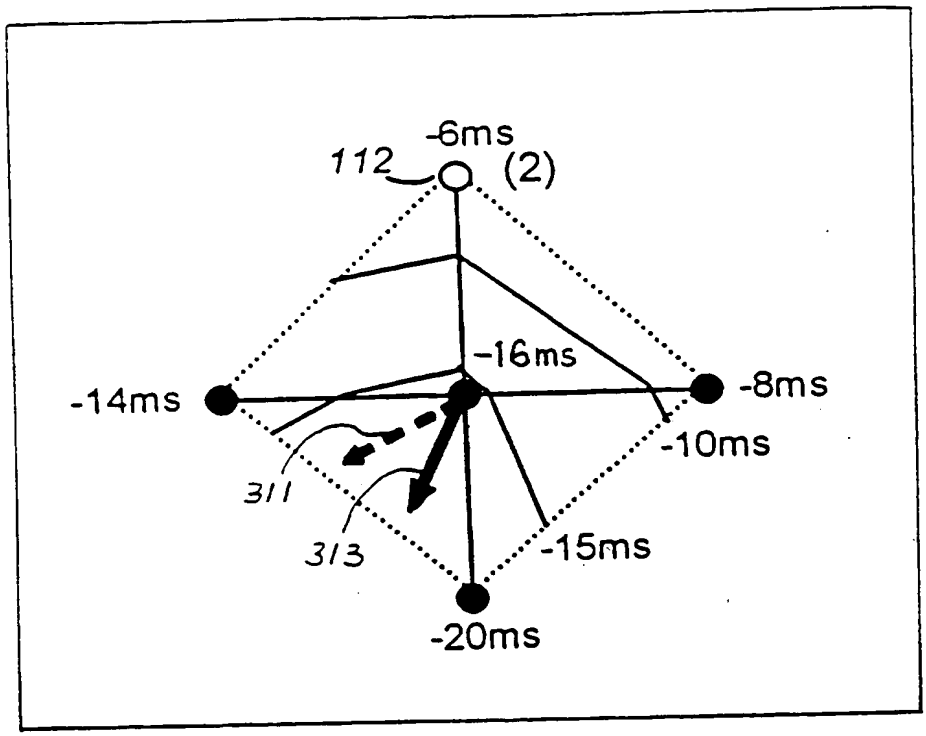

FIG. 6C

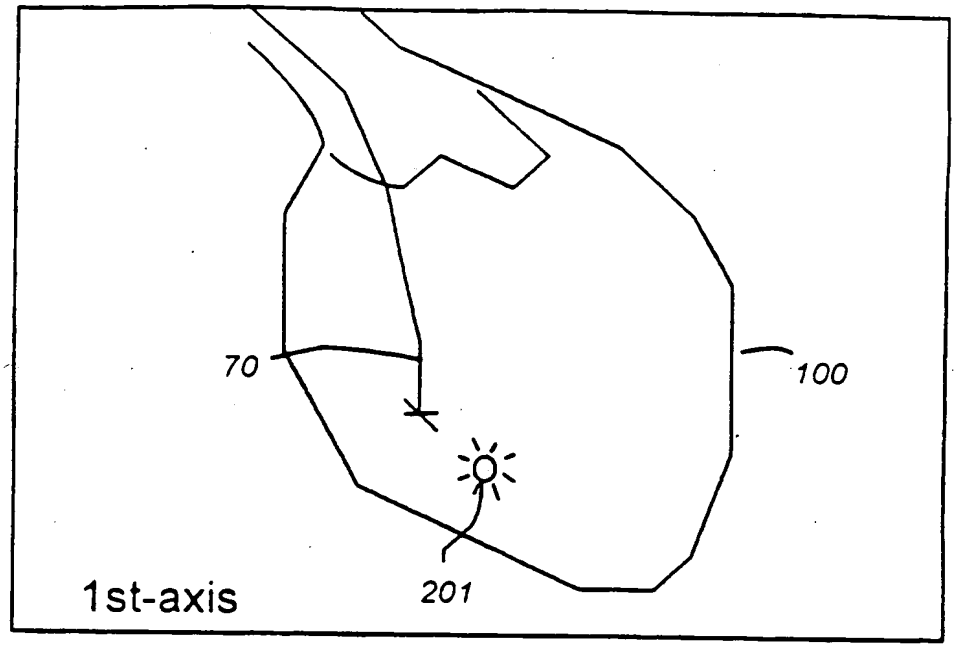

FIG. 7A

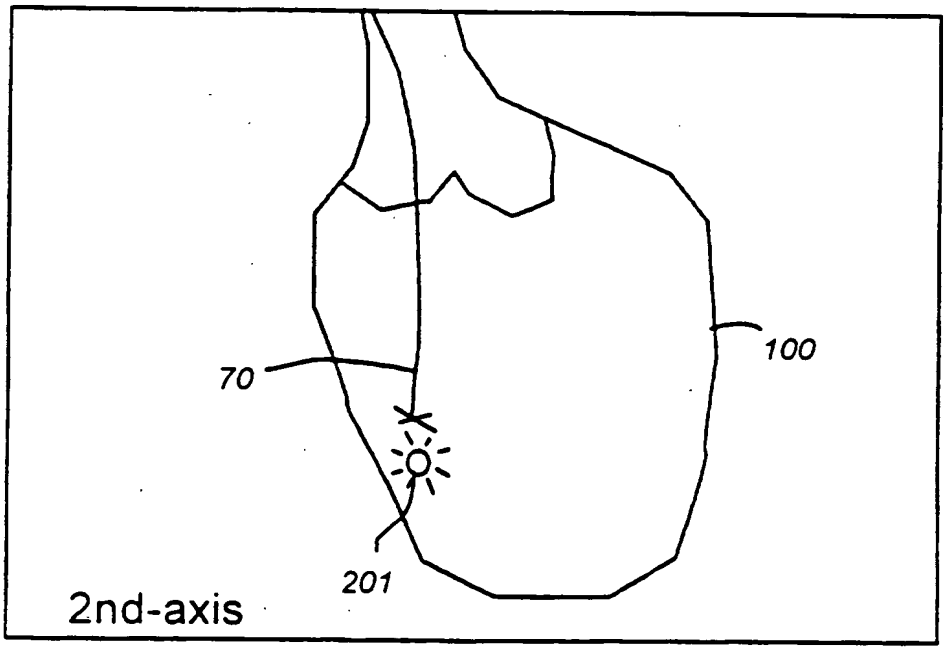

FIG. 7B

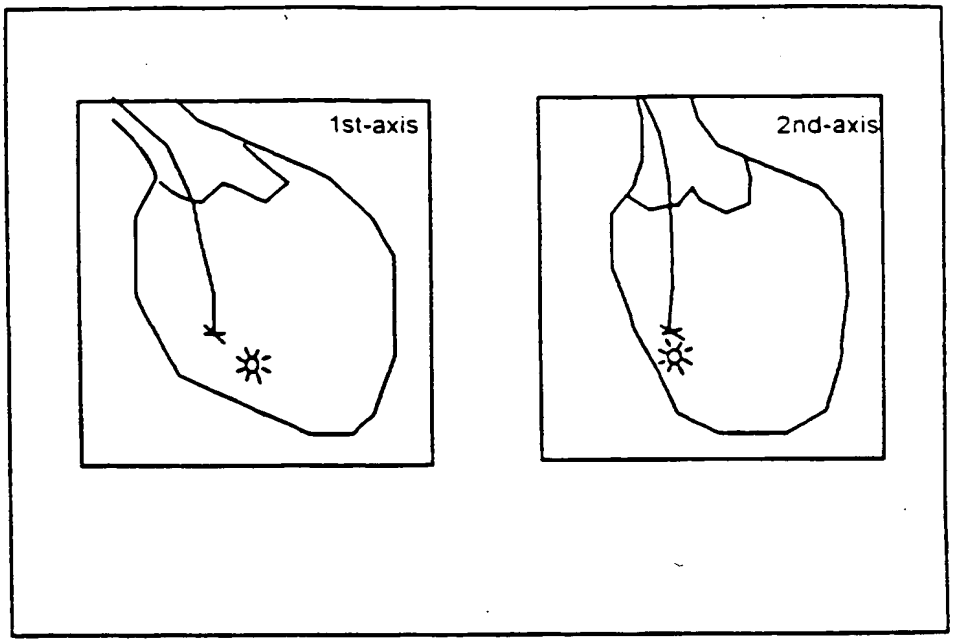

FIG. 8

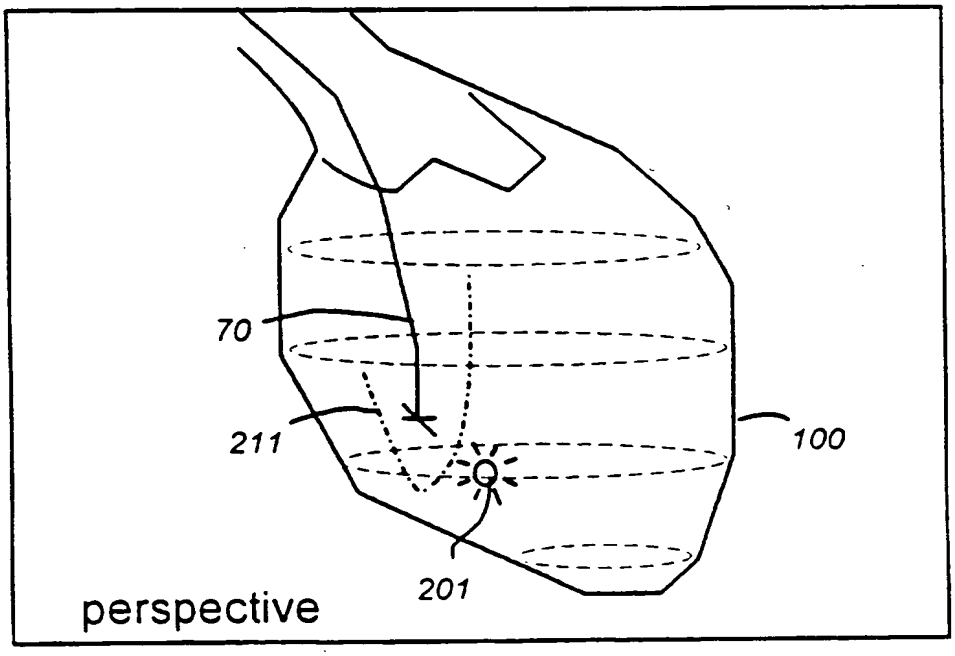

FIG. 9

INTERNATIONAL SEARCH REPORT

Inter nal Application No
PCT/US 96/05443

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 A61B5/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP,A,0 499 491 (CARDIAC PATHWAYS) 19 August 1992 see abstract see column 11, line 25 - line 43; figure 1	1
P,X	US,A,5 494 042 (PANESCU) 27 February 1996 see figure 21A	1
X	WO,A,94 06349 (ENOCARDIAL THERAPEUTICS) 31 March 1994 "two dimensional maps" see abstract	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
31 July 1996	07. 08. 96

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax (+ 31-70) 340-3016	Papone, F

Form PCT/ISA/210 (second sheet) (July 1992)

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INTERNATIONAL SEARCH REPORT

information on patent family members

Inter nal Application No
PCT/US 96/05443

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
EP-A-499491	19-08-92	US-A-	5156151	20-10-92
		AU-B-	662119	24-08-95
		AU-B-	1088992	20-08-92
		CA-A-	2061219	16-08-92
		JP-A-	7178113	18-07-95
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		US-A-	5406946	18-04-95
		US-A-	5425364	20-06-95
		US-A-	5456254	10-10-95
		US-A-	5404638	11-04-95
		US-A-	5465717	14-11-95
		US-A-	5279299	18-01-94
		US-A-	5228442	20-07-93
US-A-5494042	27-02-96	WO-A-	9520346	03-08-95
WO-A-9406349	31-03-94	US-A-	5311866	17-05-94
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		CA-A-	2144973	31-03-94
		EP-A-	0661948	12-07-95
		JP-T-	8501477	20-02-96

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